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Validation Test Report for Delft3D

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14. ABSTRACT This report describes the model setup, parameter selection and model validation of the Delft3D modeling system in nearshore applications. Delft3D, developed by Delft Hydraulics, is a complete coastal hydrodynamic modeling system, capable of simulating hydrodynamic processes due to waves, tides, river flow, and winds. Three high-fidelity observation data sets are used for validation tests. The first data set is from the Nearshore Sediment Transport Study (NSTS) data at Santa Barbara, CA (straight and steeper slope beach profile). The second data set uses data from the Duck 94 field experiment conducted at Duck, NC (barred beach profile). The third data set is from the SandyDuck97 field experiment. In general, Delft3D has been shown to be robust and accurate in predicting nearshore wave height and flows. A sample comparison between Delft3D and NSSM (Navy Standard Surf Model) is also included.					
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1. INTRODUCTION

The one-dimensional Navy Standard Surf Model (NSSM) has been widely used to produce operational surf forecasting parameters as specified in Joint Surf Manual (COMNAVSURF, 1987). The parameters include maximum and significant breaker height, breaker types, percentage of breaking, surf zone width, number of surf lines and modified surf index. The accuracy of the surf forecast depends on model performance of waves and longshore currents. NSSM has been shown to be very robust (Hsu et al., 2002), but it has its limitations. Since NSSM assumes parallel bottom contours in the surf zone (generally depths of 8 m or less), it cannot account for longshore variations of bathymetry or forcing. NSSM could produce inaccurate wave and current estimations for areas with complicated bathymetry in which case a two-dimensional nearshore wave and flow model would be more appropriate. The Delft3D modeling system, developed by Delft Hydraulics (www.wldelft.nl), is capable of simulating hydrodynamic processes due to waves, tides, river flow, and winds for any coastal area. The objectives of the NRL effort are: 1) to validate the wave and longshore current performance of Delft3D, 2) to investigate the model sensitivity to model options and free parameters and provide recommendations for operational applications, 3) to identify limitations and/or weaknesses, and 4) to produce standard surf forecast parameters and develop operational scripts.

Using measurements at Egmond/Netherlands, hydrodynamic validation of Delft3D was reported by Elias et al. (2000). Using a version of Delft3D with roller dynamics (explained later), Morris (2001) has shown that Delft3D produces good results when compared with DELILAH (Duck Experiment on Low-frequency and Incident-band Longshore and Across-shore Hydrodynamics) and limited Duck94 data at Duck, North Carolina, and Torrey Pines and Santa Barbara data in California. In recent years, many improvements including the addition of the Neumann boundary for the side boundaries (Roelvink and Walstra, 2004) have been implemented in Delft3D.

This report describes the model setup, parameter selection and model validation. Due to the large number of model options and free parameters in Delft3D, it became necessary to evaluate Delft3D sensitivity to those selections before the validation work. A report entitled “Evaluation of Delft3D Performance in the Nearshore Flows” (Hsu et al., 2006a) documents the comparison results and recommendations (see section 3.4). The evaluation includes: roller, breaking dissipation formulation, breaker delay, roller stress options in shallow-water, and three bottom roughness selections. The choice of model parameters used in this report is based on those sensitivity studies.

Three high-fidelity observation data sets are used for validation tests. The first data set is from the Nearshore Sediment Transport Study (NSTS) data at Santa Barbara, CA (straight and steeper slope beach profile). The second data set uses the October 1994 data from the Duck94 field experiment conducted at Duck, NC (barred beach profile). The third data set uses September and October 1997 data from the SandyDuck97 field experiment.

2. MODEL AND INPUT DESCRIPTIONS

The Delft3D system uses two main modules for simulating nearshore wave-induced hydrodynamic processes. The WAVE module includes the SWAN (Simulating WAVes Nearshore) model for computing propagation and generation of waves. SWAN model has been validated by Allard et al. (2004). Hydrodynamic flow is simulated with the FLOW module, which solves the unsteady shallow water equations in two (depth-averaged) or three dimensions. For applications with dominant wave-induced flow, only the two-dimensional mode is used in this report. The three-dimensional mode of wave-driven flow is still in research mode and is not recommended for operational use.

3. FIELD DATA DESCRIPTIONS AND MODEL SETUP

In this report, all four cases of NSTS at Santa Barbara (steep and planar beach profile) are used. From Duck94 data (barred beach profile), 116 cases are used. From SandyDuck97 data, 176 cases are used for validation.

3.1 Santa Barbara Cases

There are four cases from the NSTS field experiments at Leadbetter Beach, Santa Barbara, California in February 1980. The offshore waves consisted mainly of moderate swells with narrow banded frequency incident from the northwest. Significant wave height, direction (relative to beach) and period are shown in Fig. 1. The beach was planar in longshore (no cusps) and no offshore bar, the depth contours were nearly straight and parallel to the beach (see Morris, 2001). The two-dimensional bathymetry for model input was constructed based on a single trace of the beach profile. Throughout the report, the x coordinate is in the cross-shore direction and y coordinate is in the alongshore direction. The wave grid consisted of 54 points cross-shore and 71 points in alongshore with grid spacing of 2 m in cross-shore and 5 m in alongshore. The flow grid is smaller than the wave grid consisting of 52 columns and by 41 rows, at the same grid resolution. The bathymetry input is tide corrected. No directional wave spectra or wind data was available. The model input consists of parameterized wave with height, peak direction and peak wave period.

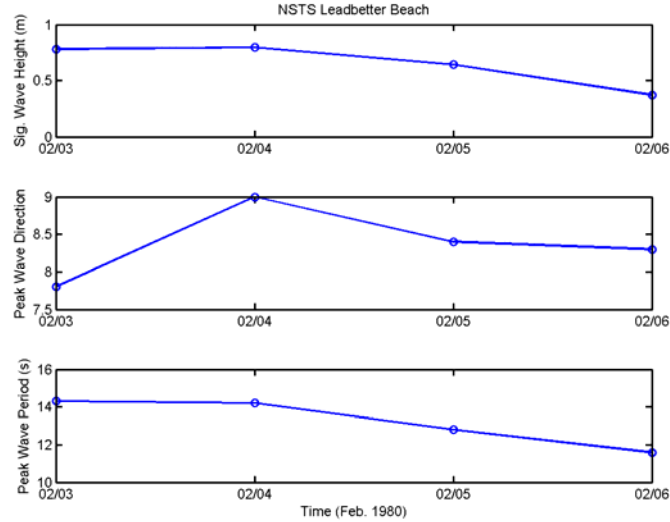


Fig. 1 – Wave conditions at Leadbetter Beach in NSTS field study

3.2 Duck94 Cases

The Duck94 field experiment was conducted in August and October, 1994 near the Army Corps of Engineers' Field Research Facility pier located in Duck, North Carolina. The instrument layout is shown in Fig. 2. The so called mini-grid area is marked by the box. A bathymetry survey was conducted daily for the mini-grid area during the intensive study period in October. The wave, wind and tide conditions during October are shown in Fig. 3.

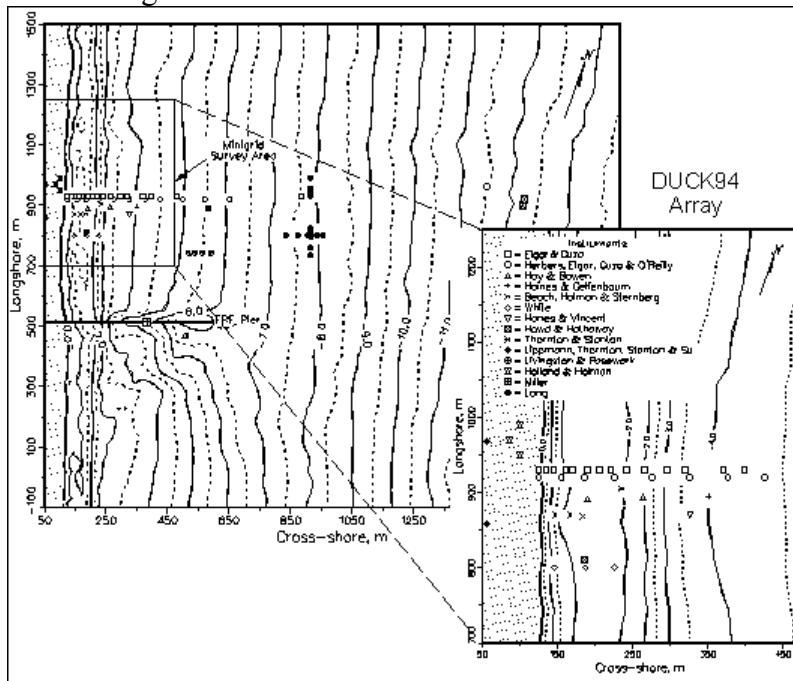


Figure 1. DUCK94 Instrument layout identified by investigator

Fig. 2 – Instrumentation layout at Duck94 (see Reference FRF94).

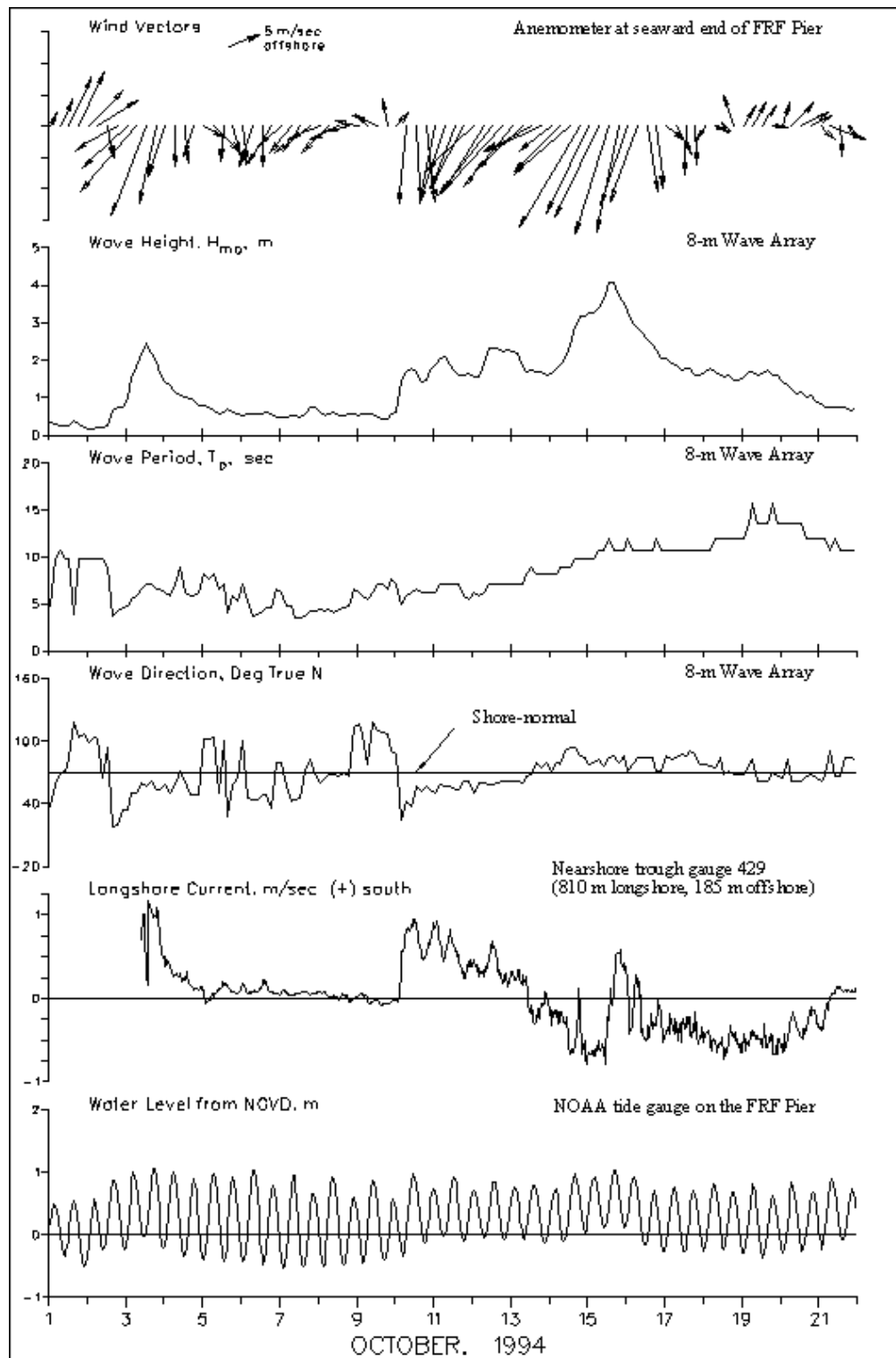


Figure 2. Conditions during the October phase of DUCK94

Fig. 3 – Environmental conditions during October 1994 (FRF94)
 Note: Wave direction from the beach facing 72 degree from North

A storm from the southeast occurred on October 15 with a peak significant wave height reaching 4 m. The beach profile was significantly changed after the storm as illustrated in Fig. 4.

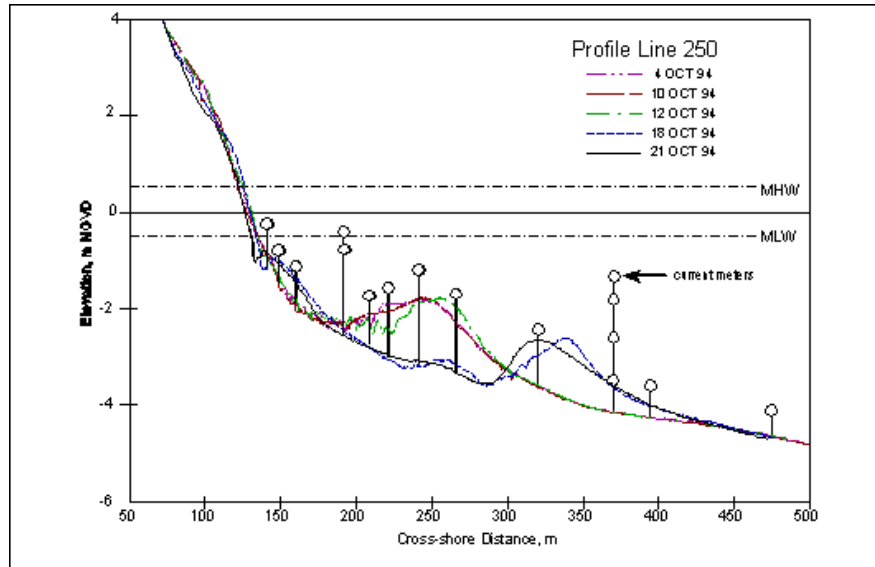


Figure 5. Profile change along the Elgar & Guza cross-shore array during DUCK94

Fig. 4 – Bottom profile changes before and after the October 15 storm (FRF94).

The WAVE model grid consisted of 86 columns and 131 rows with grid spacing of 10 m in the cross-shore direction (x), and 15 m along the shore (y). The offshore boundary was located at the 8 m directional wave gage array. The smaller FLOW grid lay inside the WAVE domain with 86 by 117 grid points with grid spacing of 10 m in the cross-shore direction and 15 m along the shore. The dates (October 5 - 21 and October 26) chosen for model validation were based on the availability of daily mini-grid bathymetry surveys. Model runs were conducted for every three hours and 116 cases were run. Directional spectrum from the 8-m array was used as input to the wave model. A bathymetry survey for a much larger area at a coarser spacing was conducted every other month. By examining the coarser September and November survey data, little bathymetry change beyond the 5-m contour was evident. Most of the depth changes are within the mini-grid region. To build the model input depth files, the coarser data were merged with daily mini-grid data. Because of the October 15 storm, September data were used for merging for those dates before October 14 and November data were used afterwards.

3.3 SandyDuck97 Cases

The SandyDuck97 field study program was designed to improve fundamental knowledge of the natural processes that cause beaches to change (FRF94). It provides extensive nearshore wave and velocity measurements. The gage layout is shown in Fig. 5, and it contains many more cross-shore gages than that from Duck94. The primary measurement period occurred from September 22 through October 31, 1997.

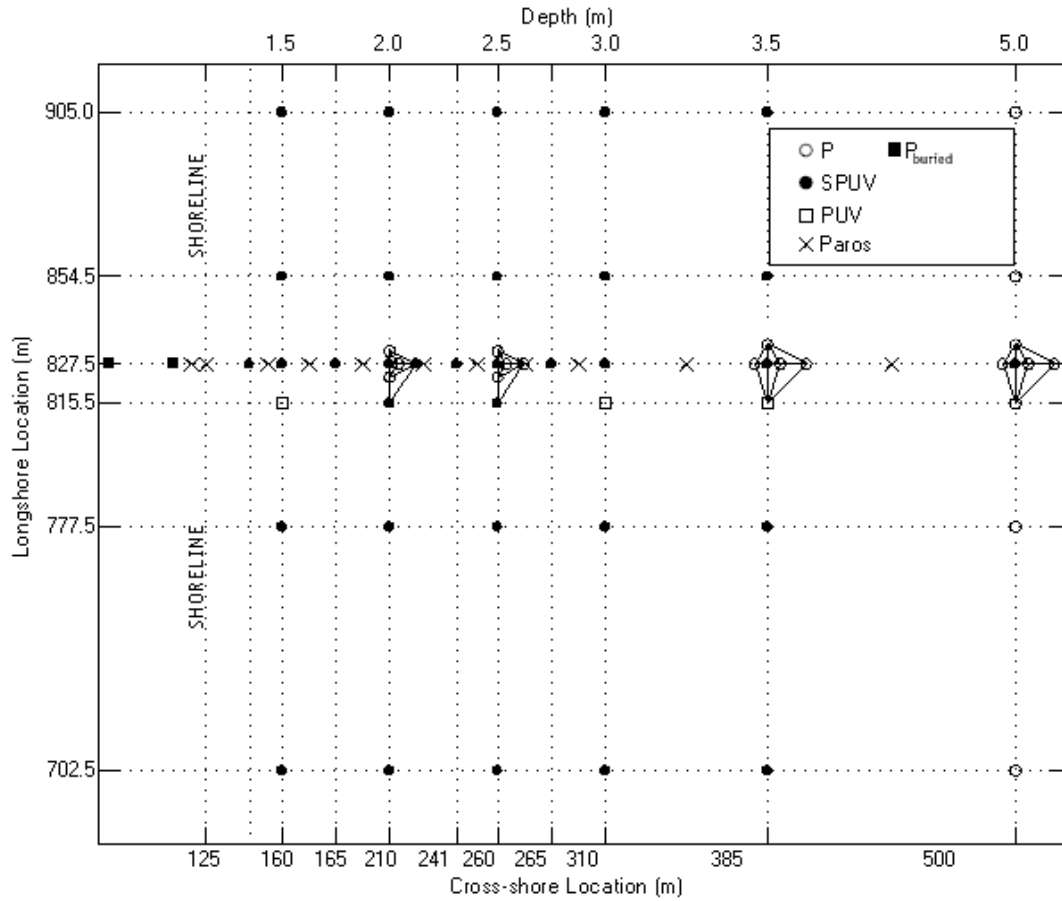


Fig. 5 – SandyDuck97 Gage Array Layout (from FRF97)

SPUV – sound altimeter (S), pressure sensor (P), bi-directional (UV) current meter

The wave conditions from three gages for September and October are plotted in Fig. 6. The time period covers several wave events including the storm around October 19-20. Our simulation starts at 1 EST (Easter Standard Time) of September 27 and ends at 22 EST of October 20 running every 3 hours, for a total of 176 cases. In the simulation period, the barred feature of winter beach profile at SandyDuck97 is much less dominant than that at Duck94.

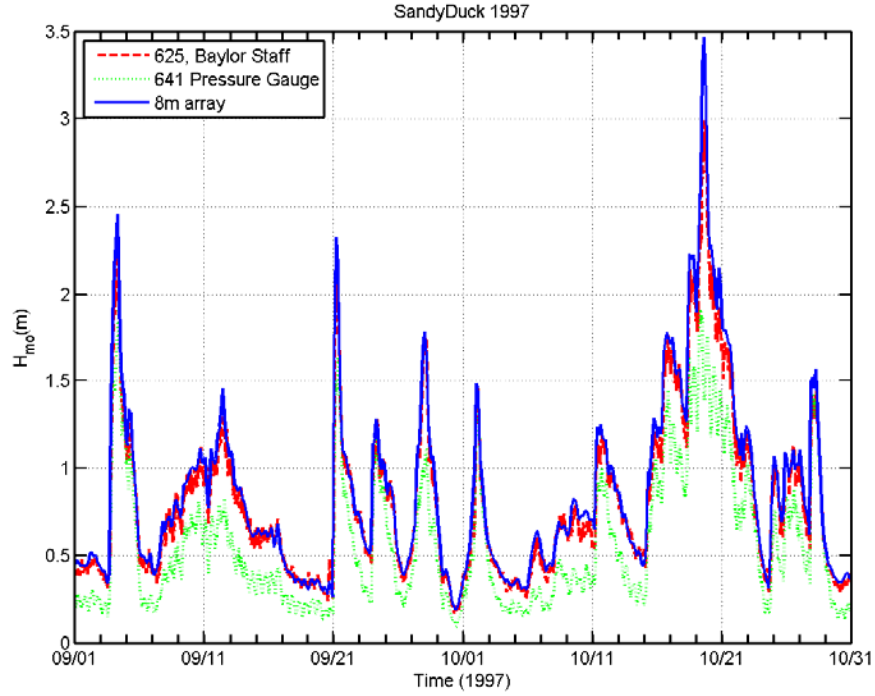


Fig. 6 – Wave conditions for SandyDuck97

The WAVE and FLOW grids are similar to the Duck94 setup except that the wave grid is larger at southern end with 86 grid points in x and 147 grid points in y, i.e. 15 more in cross-shore. In building the model depth files, longshore uniform areas are extended by a few grid points into the FLOW domain on both side boundaries. This is to satisfy the Neumann boundary condition which assumes negligible advection terms containing longshore gradient of velocity (Roelvink and Walstra, 2004). If the longshore uniform area does not extend into the FLOW domain, spurious eddies may form at the southern end where flow is exiting.

3.4 Model Parameters and Setup

3.4.1 Wave Parameters

In SWAN, the energy dissipation due to depth-induced breaking is based on the bore model of Battjes and Janssen (1978). The rate of dissipation depends on the gamma value, i.e. ratio of the maximum wave height, (H_{\max}), over depth (d), defined as

$$\gamma = H_{\max} / d \quad (1)$$

In SWAN, the default gamma value is set at 0.73 (Battjes and Stive, 1985). If the roller option is used in Delft3D, the default gamma value is 0.55. In Delft3D, a variable gamma scheme (Ruessink et al., 2003) is also available by adding a keyword Gamdis with value of -1. The scheme is defined as

$$\gamma = 0.76kd + 0.29 \quad (2)$$

where k is the wave number. In their study, the values of kd range from 0.25 to 0.75. Hsu et al. (2006a) reported that Ruessink's formulation produces better agreement in longshore current with a narrower velocity distribution profile, i.e. smaller offshore values and more peaked at velocity maximum. But no comparison of skill statistics of wave height between fixed and variable gamma was made.

In the wave setup, wave model performance under both fixed and variable gamma is evaluated in this report.

3.4.2 Flow parameters

It has been shown that all three bottom roughness formulations (Manning, White-Colebrook and Chezy) can produce good results if a proper empirical constant is chosen (Hsu et al., 2006a). The depth dependence of Manning and White-Colebrook becomes significant only when depth is shallower than 0.5 m. The default Chezy formulation is used for bottom roughness. The Chezy formulation implies a constant Chezy value (C) for the whole domain, i.e. no depth dependency. By definition, the bottom friction coefficient, C_f , is related to the Chezy roughness coefficient by

$$C_f = g / C^2 \quad (3)$$

where g is the acceleration due to gravity. The default Chezy value is set at 65 corresponding to a friction coefficient at 0.0023.

Over a barred beach, previous model and field data comparison shows that the peak longshore current occurred in the trough whereas the model peak occurred at the beginning of the bar (e.g., Kraus and Larson, 1991). The roller formulation (e.g., Smith, et al., 1993 and Ruessink et al., 2001) was proposed to delay momentum release from the wave breaking. As waves break, turbulence is generated and rushes down the front of the wave. The volume of the turbulent water was modeled as surface roller. The inclusion of surface roller model in nearshore current modeling is mainly designed to move the velocity peak towards the trough of the bar. Roller stress is turned off at 0.4 m to avoid spuriously high longshore currents. Larson and Kraus (2002) reported that a limiter was placed on their roller model to limit the growth of the roller so that the gradient in the roller momentum flux does not exceed the gradient of radiation stress.

In the Delft3D roller implementation manual, Roelvink (2003) described the roller model as follows:

- It solves a wave energy balance and roller energy balance within the FLOW model, using a trimmed-down version of the 'DIFU' advection-diffusion solver.
- Based on the wave energy and roller energy, radiation stresses and gradients of these stresses are computed that replace the conventional wave forces as derived from the WAVE model.

- The wave direction is still derived from an initial WAVE run.

To clarify the last statement, if the roller option is chosen, only the wave direction from SWAN is used and the rest of wave computations are done by the Delft3D group. The full equations for the roller and wave-driven flow model are not repeated here (Roelvink, 2003; Reniers et al., 2004).

The following flow parameters are chosen for all model runs:

- Chezy bottom roughness
- Roller on
- Roller stress turned off at 0.4 m
- No breaker delay

3.4.3 Miscellaneous

All model runs were made with Delft3D version 3.25.04. The flow code version was 1.04.03.00 with SWAN version 40.41A. The flow version was 3.54.23.00. It should be noted that same wave and flow results are produced by the latest version, i.e. version 3.26.01. Most of the latest updates are related to other features of Delft3D, such as sediment transport and domain decomposition, etc. Tests were conducted for full wave-current interactions through iterations. To save computing time, all runs were made without wave-current interactions. A comparison of skill statistics of SandyDuck97 cases with and without wave-current interactions are presented in the discussion section.

Directional wave spectra at the 8m gage array are used for wave input conditions for Duck94 and SandyDuck97. The tide level and wind was applied to both WAVE and FLOW modules. No wind was available for the Santa Barbara cases. For waves, bottom friction (using default JONSWAP type) was included, and wave diffraction and nonlinear triad interactions were turned off. Since the depth-induced breaking is the dominant process in the surf zone and the wave model domain is small, the effect of bottom friction coefficient selection is not pursued. All WAVE runs were stationary, i.e. waves do not change during the 60 minutes flow computation.

For skill statistics comparisons, model runs were conducted for

- both fixed and variable gamma (for wave height comparisons), and
- various Chezy bottom roughness ($C = 55$ at $C_f = 0.0032$, $C = 65$ at $C_f = 0.0023$ and $C = 70$ at $C_f = 0.00198$)

At least four combination of parameter selections were conducted for each data set. Neumann boundary conditions are applied to side boundaries.

4. MODEL RESULTS

4.1 Santa Barbara Cases

The comparison between fixed and variable gamma and two different bottom friction selections ($C = 65$ and $C = 70$) for all four cases are presented in Fig. 7. Model runs using $C = 55$ were also conducted. But the results show substantial under-prediction of longshore current, therefore are not shown here.

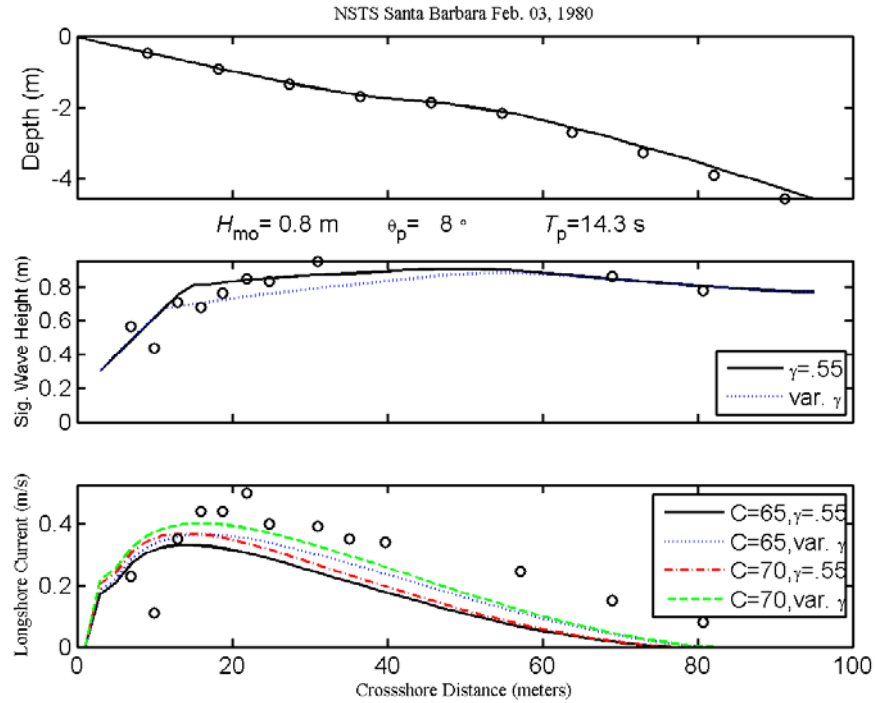
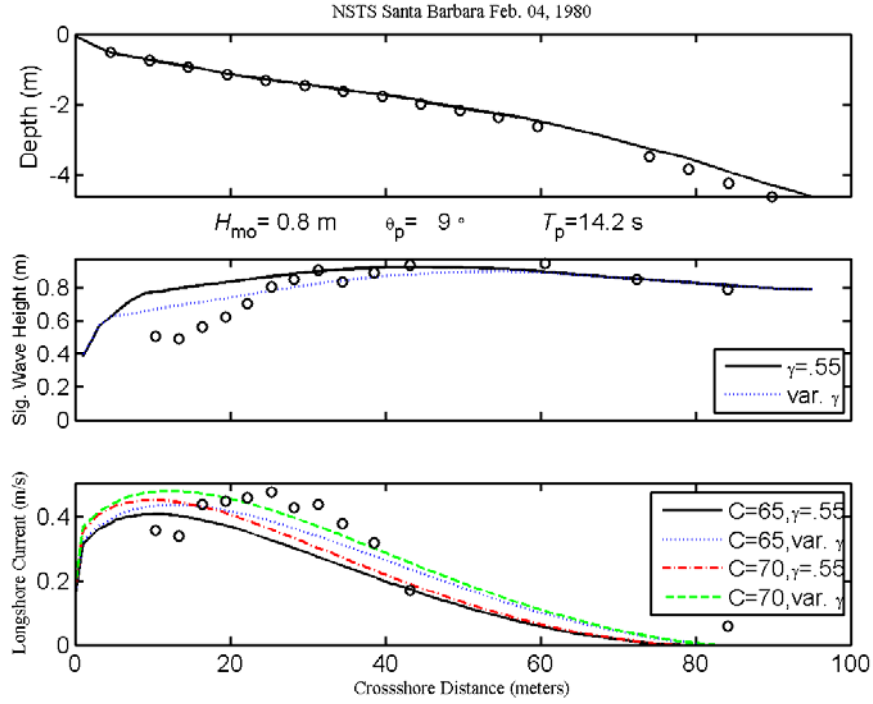
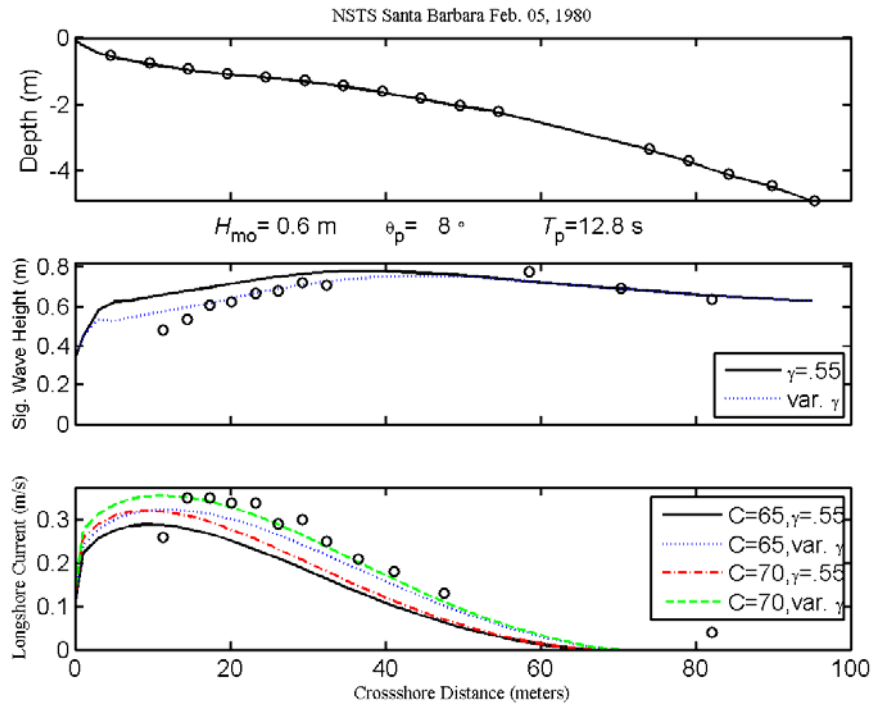


Fig. 7a – Comparison of results using fixed gamma and variable gamma at two different bottom friction values for February 03, 1980. The first panel shows the beach profile, with dots representing the actual data. The second panel shows the significant wave height comparison between fixed and variable gamma. The third panel shows the longshore current comparison between cases using different bottom friction values under fixed and variable gamma.

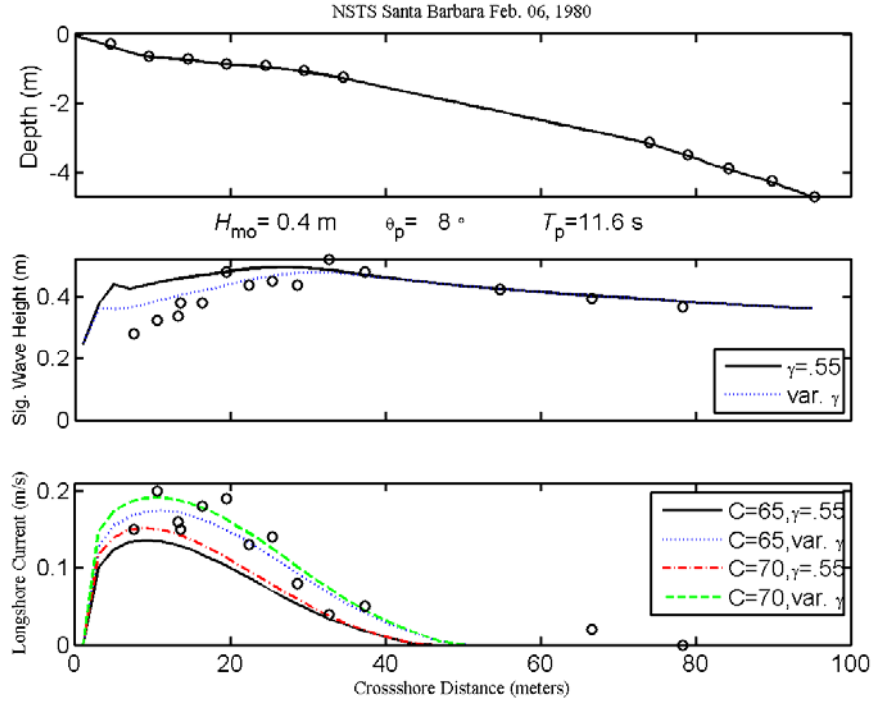


(b) February 04, 1980



(c) February 05, 1980

Fig. 7b-c – Comparison of results using fixed gamma and variable gamma at two different bottom friction values for February 04 and 05, 1980.



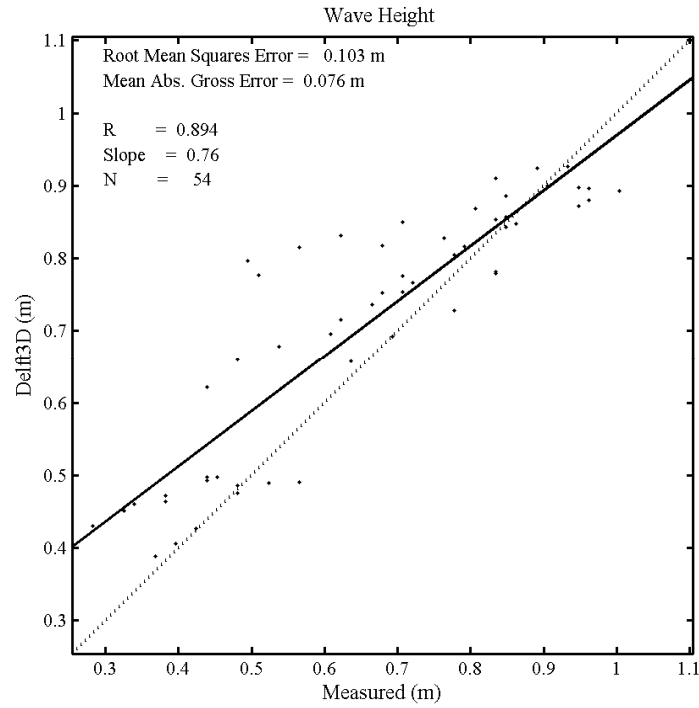
(d) February 06, 1980

Fig. 7d – Comparison of results using fixed gamma and variable gamma at two different bottom friction values for February 06, 1980.

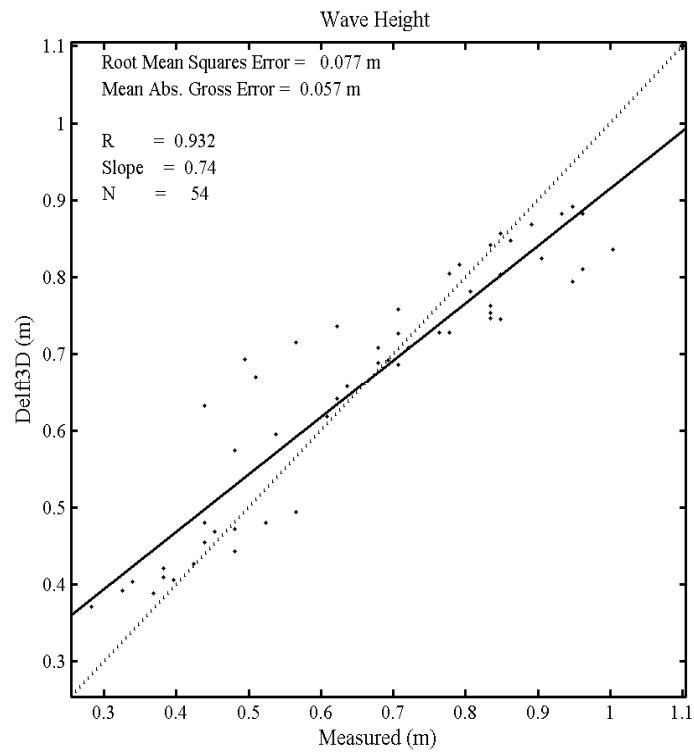
In general, wave height results from both fixed and variable gamma schemes agree reasonable well (see scatter plot presented below) with measurement except at very shallow depths. The longshore current results using the default Chezy value of 65 slightly under-predict the current.

4.1.1 Skill Statistics for Significant Wave Height

The scatter plot for significant wave height for both fixed and variable gamma is shown in Fig. 8. The skill statistics for wave height are summarized in Table 1. In addition to root mean square error (RMSE), mean absolute gross error (MAGE) is also listed. R represents the linear correlation coefficient and slope is the slope of the linear regression line (solid line). N is the number of observations. Wave height results using variable gamma show slightly better agreement with data.



(a) Fixed gamma



(b) Variable gamma

Fig. 8 – Scatter plots of significant wave height under fixed and variable gamma

Table 1 – Skill statistics of significant wave height at Santa Barbara

	RMSE(m)	MAGE (m)	R	Slope	N
Fixed $\gamma = 0.55$	0.103	0.076	0.89	0.76	54
Variable γ	0.077	0.057	0.932	0.74	54

To examine the error distribution further, the RMSE is broken into height bins and normalized by mean of the bin. In Fig. 9, the normalized error, RMSE/Mean, is plotted in 0.25 m bins. The normalized errors at low wave height bins are amplified by dividing with a small mean value. In other words, a 0.1 m RMSE at the 0.1 m bin gives 100% normalized error whereas the same error at 0.5 m bin gives 20% error. The average value of the normalized errors for wave heights above 0.5 m from Fig. 9 is 13%.

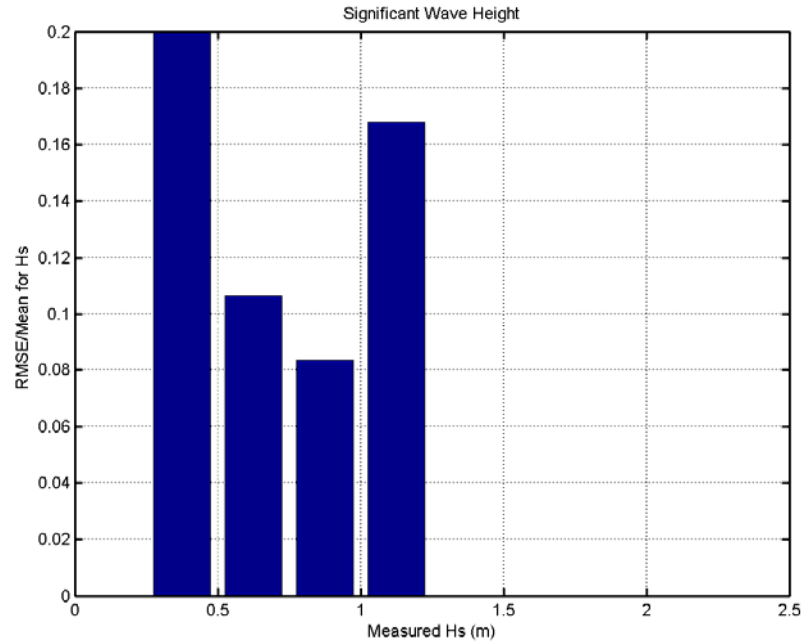
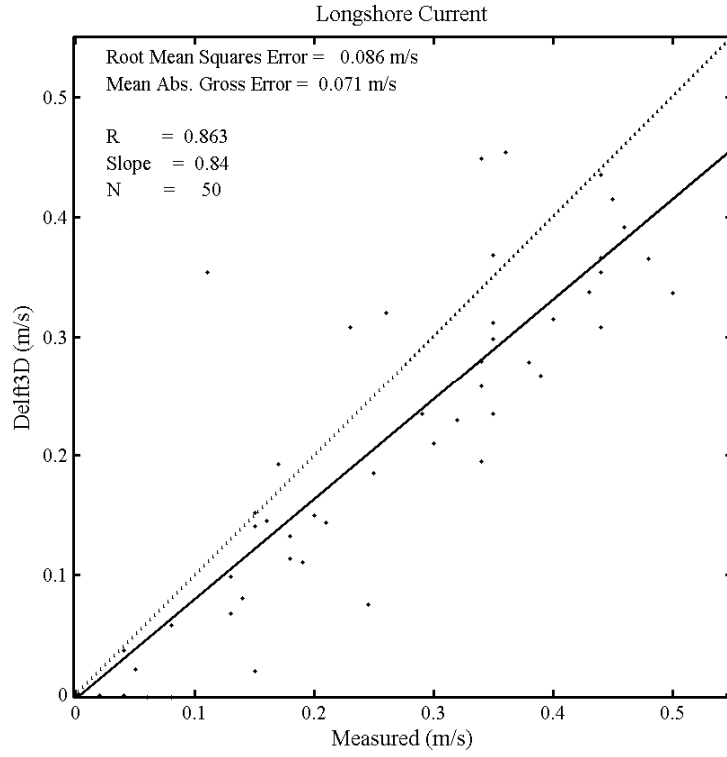


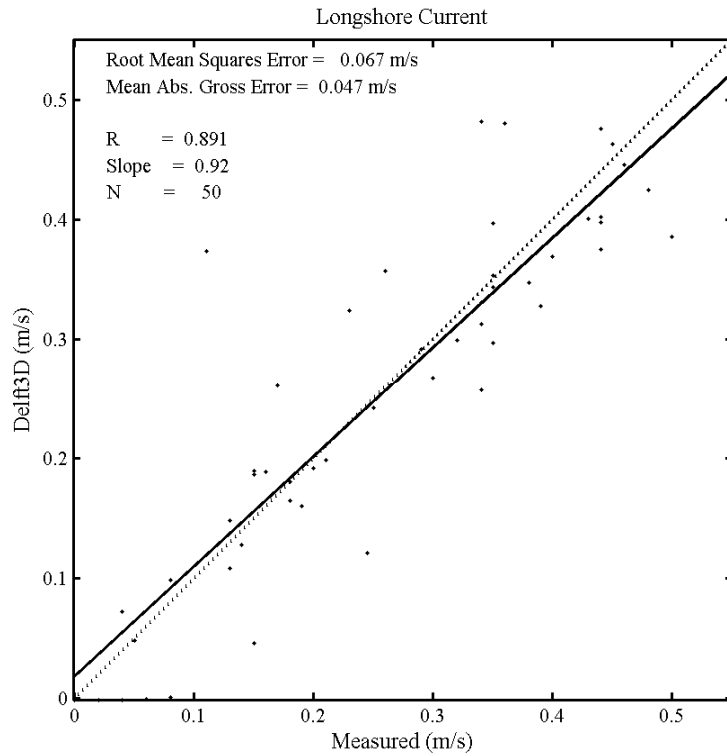
Fig. 9 – Normalized error (RMSE/Mean) for significant wave height at variable gamma

4.1.2 Skill Statistics for Longshore Current

The scatter plots for longshore current for both fixed and variable gamma at $C=70$ are shown in Fig. 10. The skill statistics for longshore currents are summarized in Table 2. Using the default bottom friction of $C=65$ ($C_f = 0.0023$), longshore current results show a slightly under-prediction. Better results are obtained by using $C=70$ ($C_f = 0.002$).



(a) $C = 70$, fixed gamma



(b) $C = 70$, variable gamma

Fig. 10 – Scatter plots of longshore current with $C=70$ under fixed and variable gamma

Table 2 – Skill statistics for longshore current at Santa Barbara

	RMSE(m/s)	MAGE (m/s)	R	Slope	N
$C=65$, fixed γ	0.097	0.082	0.865	0.76	50
$C=65$, variable γ	0.068	0.053	0.895	0.84	50
$C=70$, fixed γ	0.086	0.071	0.863	0.84	50
$C=70$, variable γ	0.067	0.047	0.891	0.92	50

The normalized error for 0.05 m/s bins for longshore current is shown in Fig. 11. The average value of the normalized errors for current above 0.2 m/s is 21%.

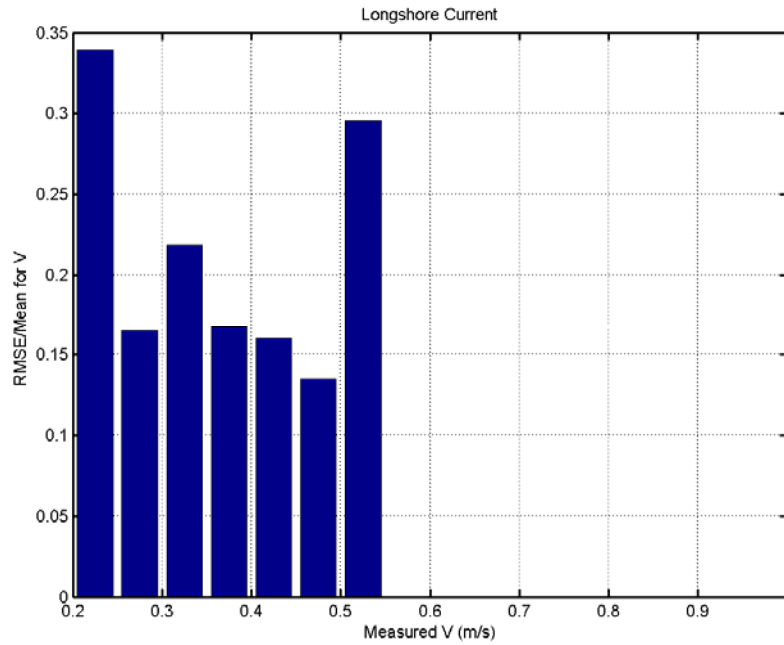


Fig. 11 – Normalized error (RMSE/Mean) for longshore current with $C = 65$ and variable gamma.

4.2 Duck94 Cases

Although model runs are made for October 5 - 21 and 26 at 3-hourly intervals, only sample results are shown in Fig. 12. Both low- and high-tide cases as well as cases when waves came from both the northeast and southeast were chosen. Cases were also chosen based on the occurrence of storms, i.e. before and after the October 15 storm. Below the first panel in Fig. 9, the tide and wind parameters are listed. The nautical convention for wind direction (i.e. arriving clockwise from North) is used. Below the second panel, incoming wave parameters are listed. The wave direction represents azimuths from which waves arrive in degrees counterclockwise from normal to the array, or approximately from shore normal which is our x axis. Zero degree represents waves propagating straight onshore. A direction of +45 degrees indicates waves coming from the northeastward side of the pier, and propagating along an azimuth 45 degrees to the left of the pier axis (x axis) for an observer looking seaward. All measured significant

wave height and current speed represent hourly averaged data. The flow sign convention of the data is positive for southern flow, so Delft3D result is adjusted accordingly.

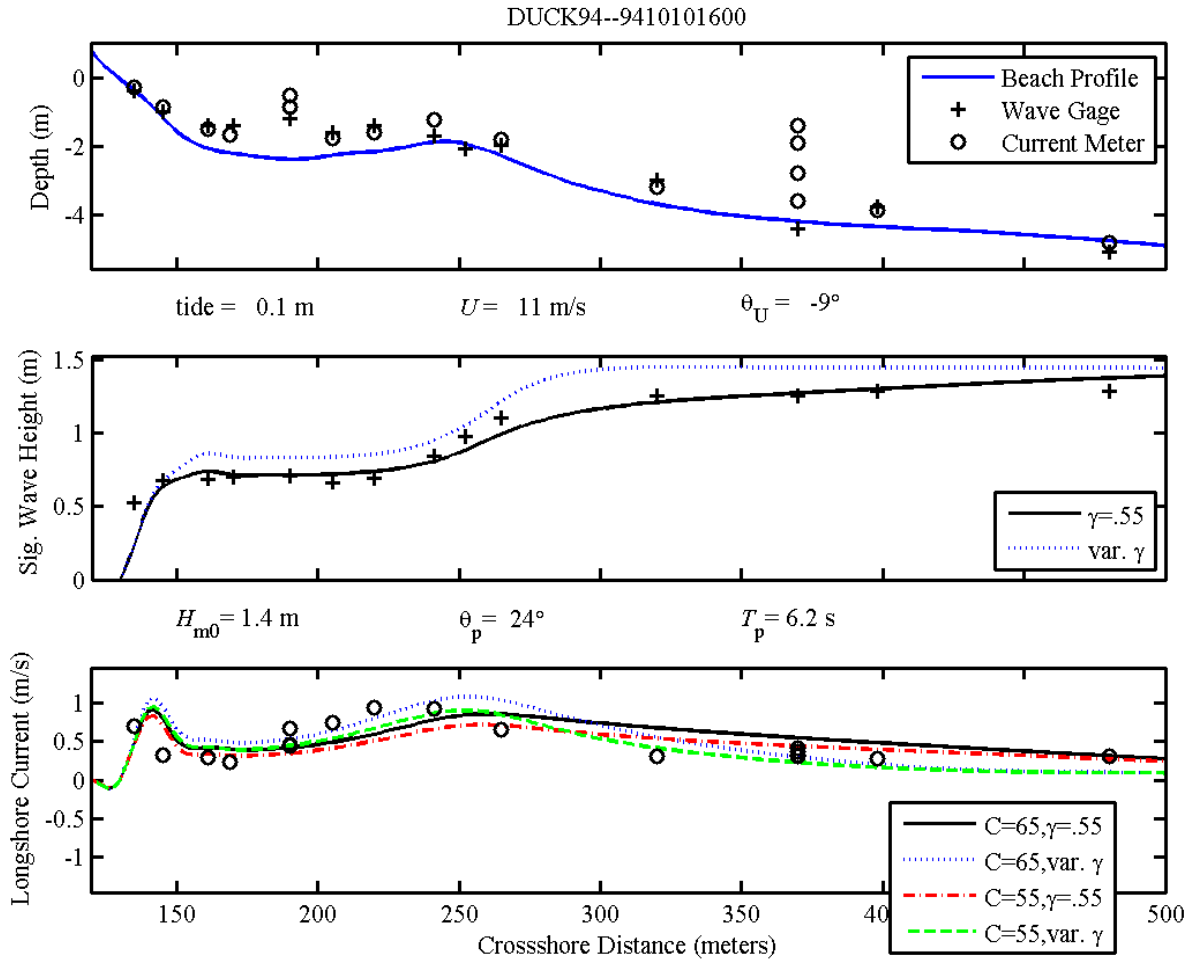


Fig. 12a – Comparison of results using fixed gamma and variable gamma and two different bottom friction values for October 10, 16 EST.

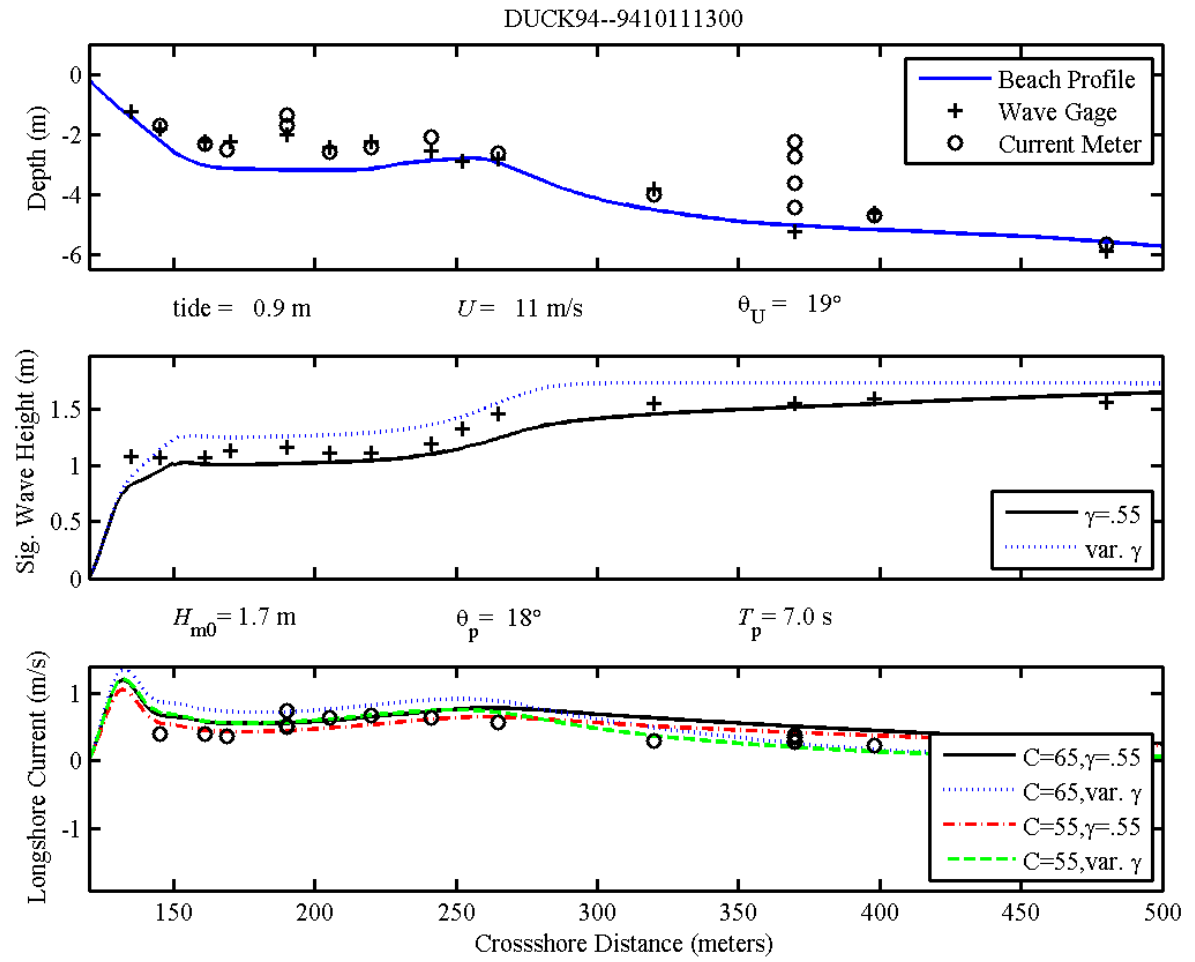


Fig. 12b – Comparison of results using fixed gamma and variable gamma and two different bottom friction values for October 11, 13 EST.

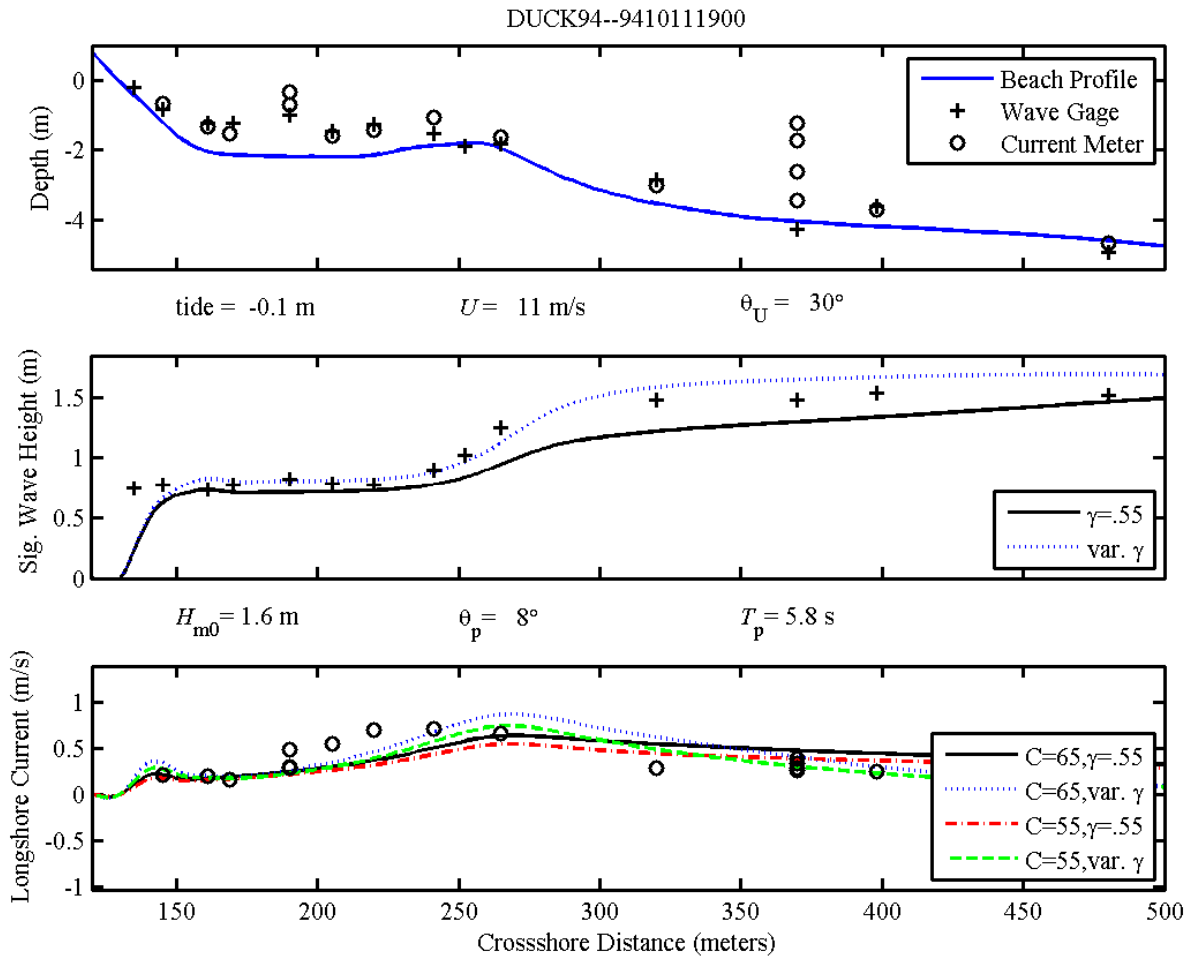


Fig. 12c – Comparison of results using fixed gamma and variable gamma and two different bottom friction values for October 11, 19 EST.

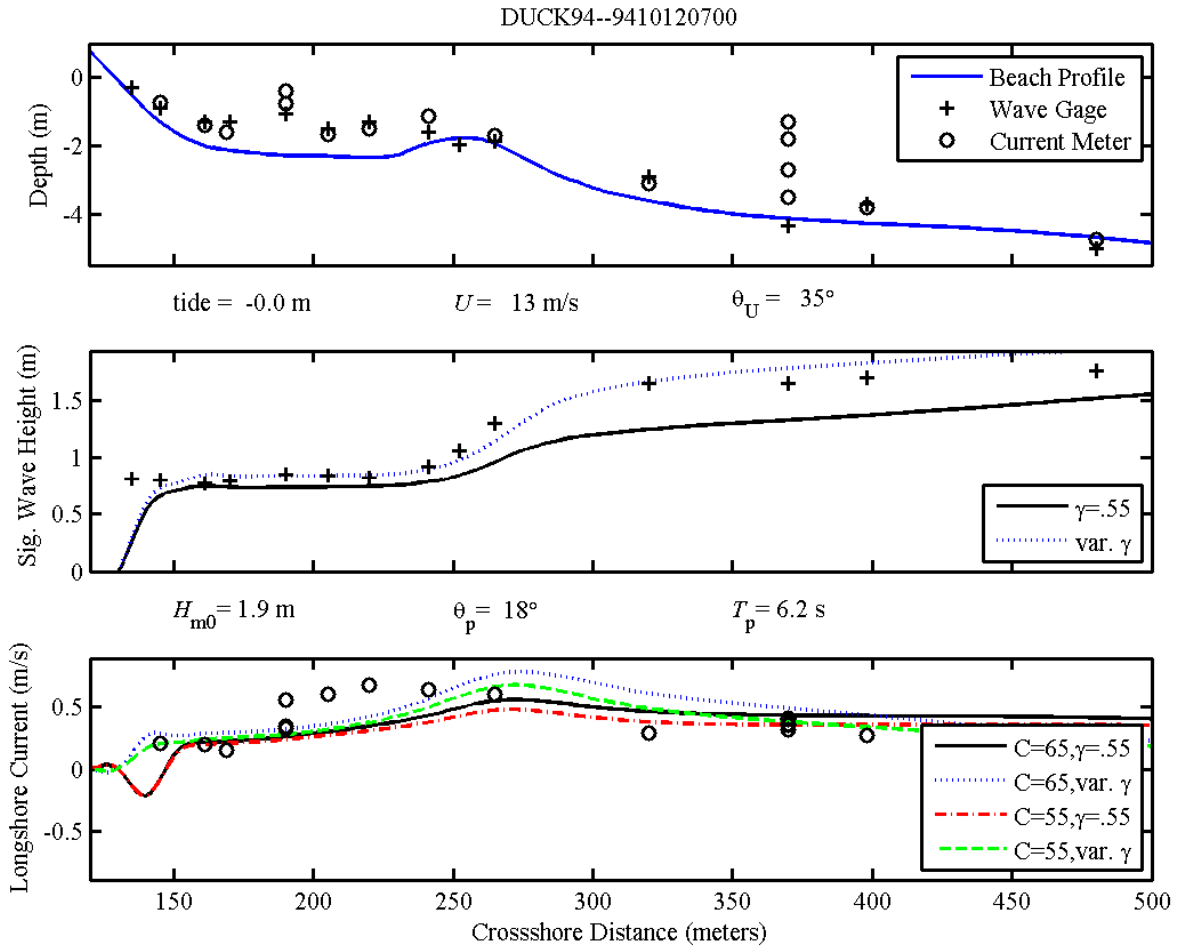


Fig. 12d – Comparison of results using fixed gamma and variable gamma and two different bottom friction values for October 12, 07 EST.

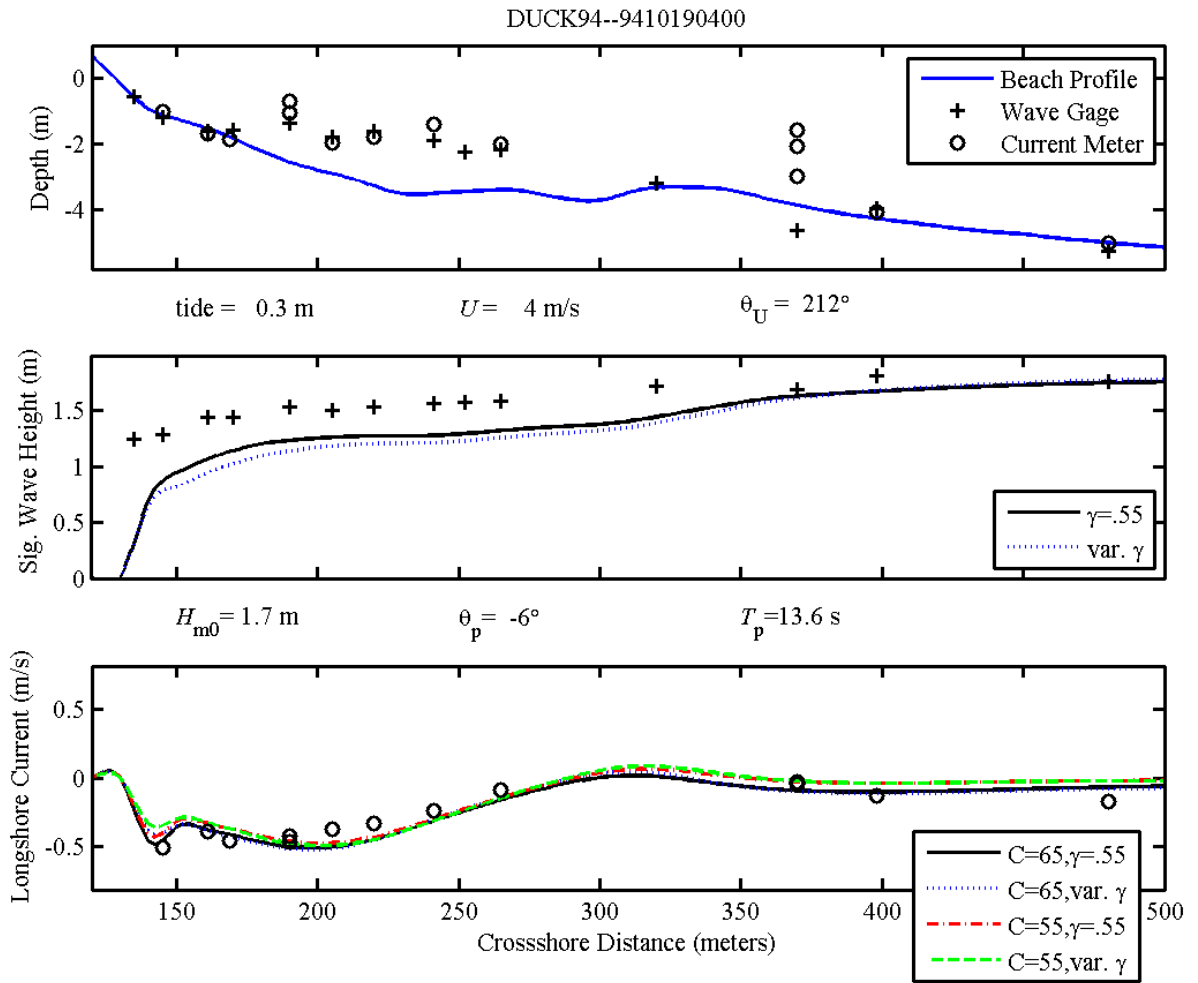


Fig. 12e – Comparison of results using fixed gamma and variable gamma and two different bottom friction values for October 19, 04 EST.

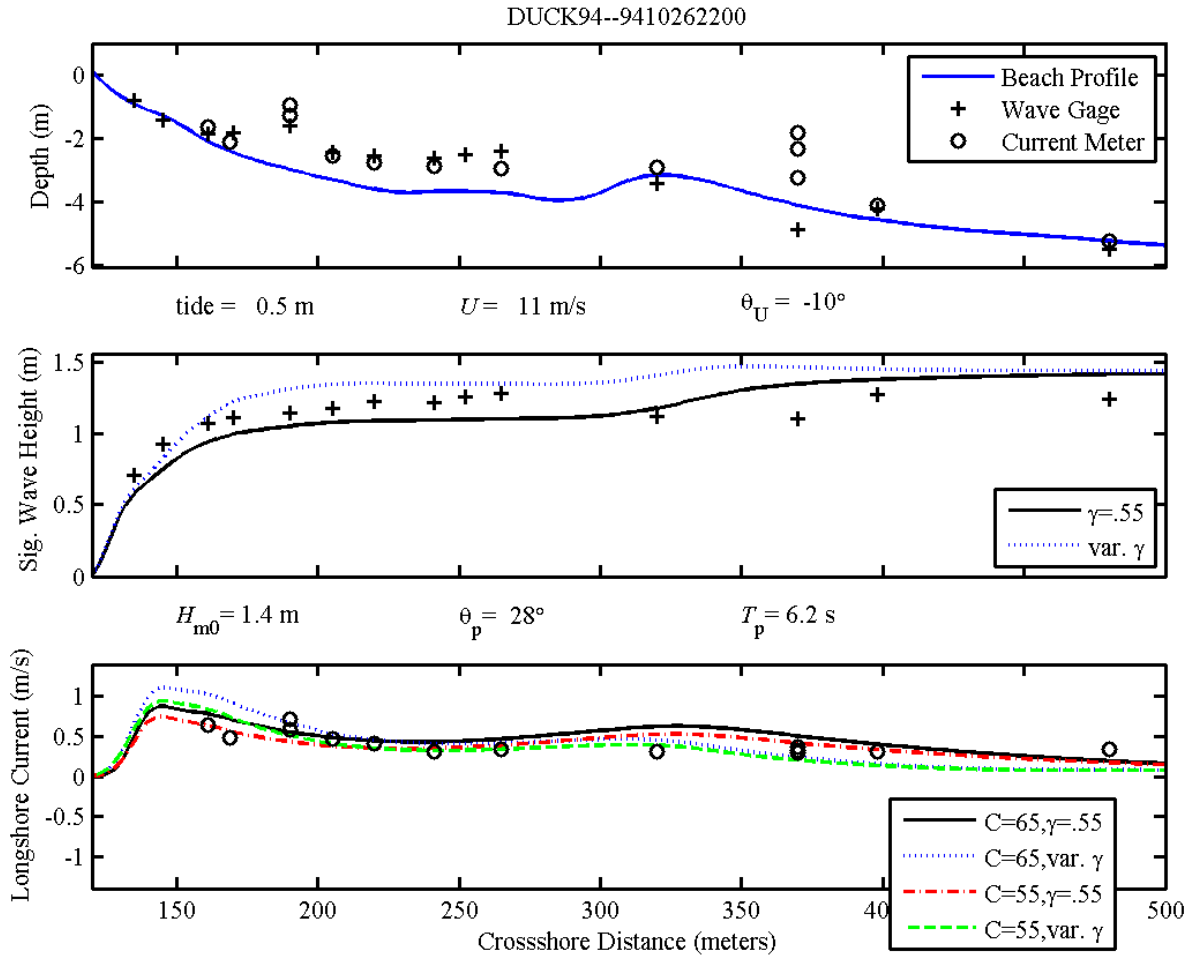
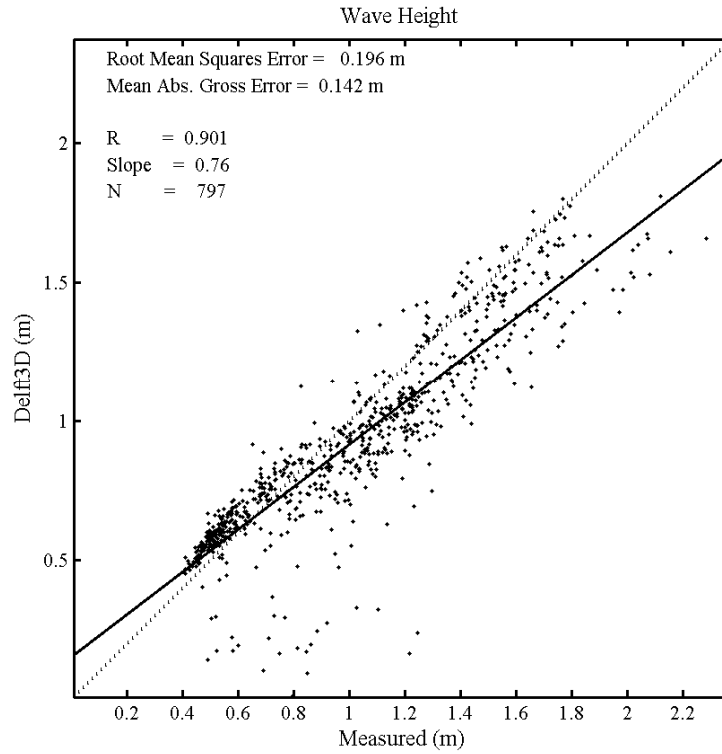


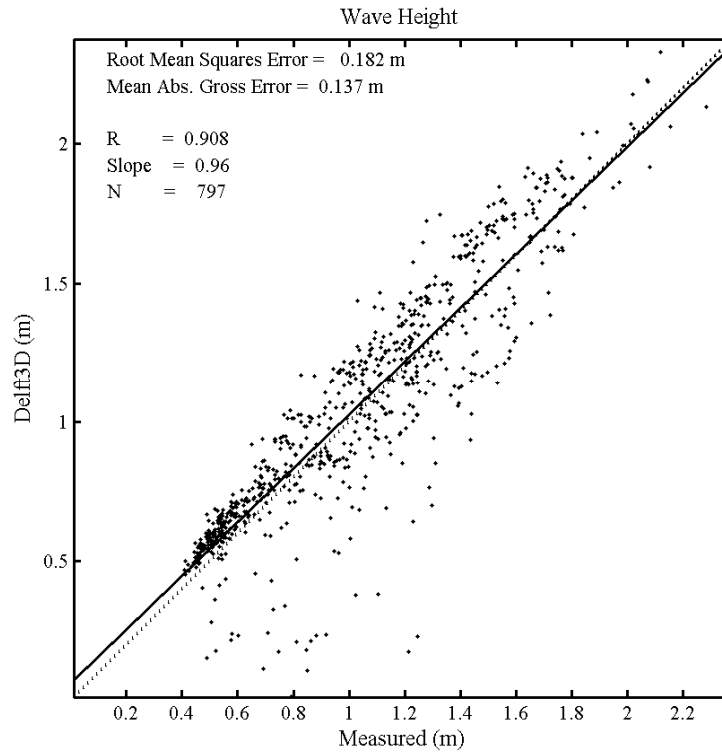
Fig. 12f – Comparison of results using fixed gamma and variable gamma and two different bottom friction values for October 26, 22 EST.

4.2.1 Skill Statistics for Significant Wave Height

For computing the skill statistics, 56 out of the computed 116 cases of Duck94 data were used. The cases with low waves (less than 0.6 m offshore) or rip current were not included. The rip current cases were identified by examining the two-dimensional current plot. The scatter plots for significant wave height are presented in Fig. 13. The skill statistics for wave height is summarized in Table 3. For wave height, the agreement is very good for variable gamma with a correlation coefficient at 0.92, slope (linear regression line) of 0.96 and RMS error at 0.18 m. The slope for fixed gamma is only 0.76, indicating it is set too low. In other words, waves are too low (see Equation 1) due to low value of gamma.



(a) Fixed gamma



(b) Variable gamma

Fig. 13 – Scatter plots for significant wave height

Table 3 – Skill statistics of significant wave height at Duck94

	RMSE(m)	MAGE (m)	R	Slope	N
Fixed γ	0.20	0.14	0.91	0.76	797
Variable γ	0.18	0.13	0.92	0.96	797

In Fig. 14, the normalized error, RMSE/Mean, is plotted in 0.25 m bins. The average value of the normalized errors for wave heights above 0.5 m is 11%.

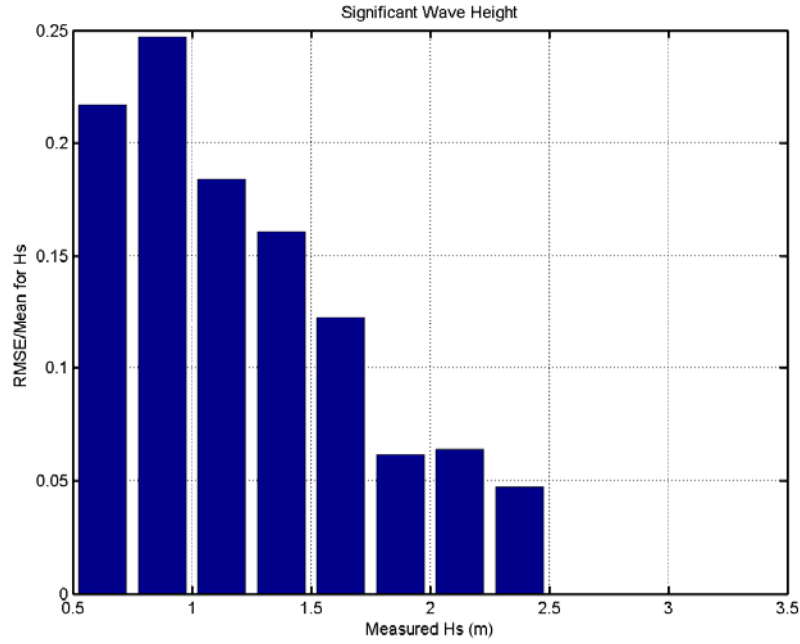
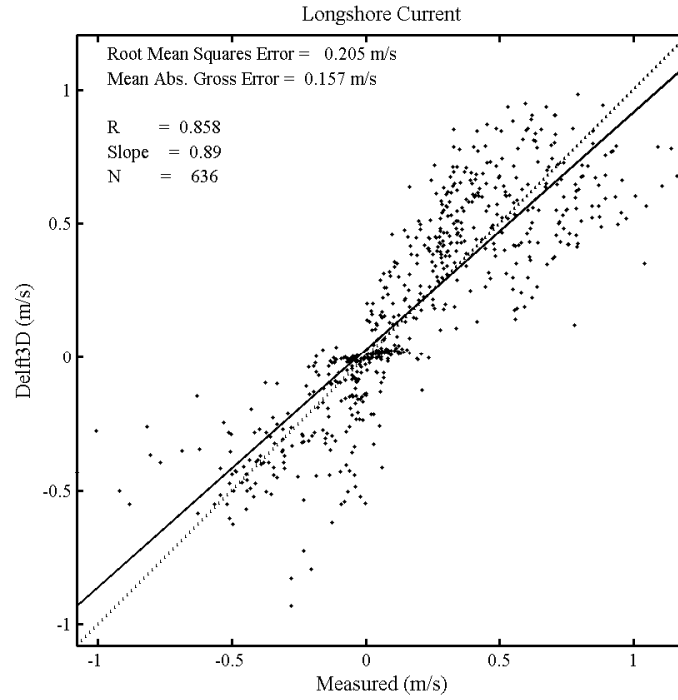


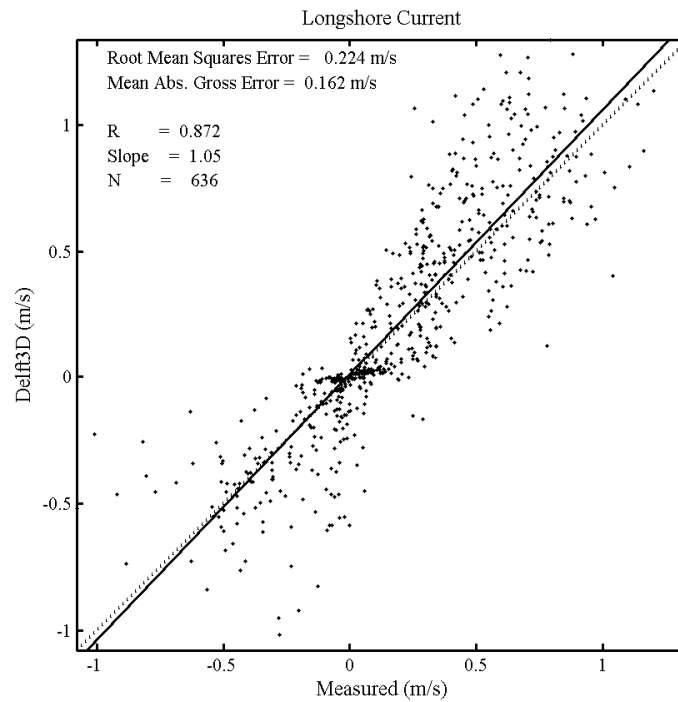
Fig. 14 – Normalized error (RMSE/Mean) for significant wave height at variable gamma.

4.2.2 Skill Statistics for Longshore Current

The scatter plots for longshore current with $C = 65$ with fixed and variable gamma are shown in Fig. 15. The skill statistics for longshore current are summarized in Table 4. The RMS error of longshore current at default Chezy $C = 65$ ($C_f = 0.0023$) is close to that at $C = 55$ ($C_f = 0.0032$), but the slope of the linear regression is 1.05 vs. 0.85. The overall performance of the longshore current with $C = 65$ is better.



(a) $C=65$ and fixed gamma



(b) $C = 65$ and variable gamma

Fig. 15 – Scatter plots for longshore current with $C = 65$ with fixed and variable gamma.

Table 4 – Skill statistics of longshore current at Duck94

	RMSE(m/s)	MAGE (m/s)	R	Slope	N
$C=65$, fixed γ	0.21	0.157	0.86	0.89	636
$C=65$, variable γ	0.22	0.162	0.87	1.05	636
$C=55$, fixed γ	0.20	0.142	0.86	0.73	636
$C=55$, variable γ	0.19	0.140	0.87	0.85	636

The normalized error for 0.1 m/s bins for longshore current is shown in Fig. 16. The average value of the normalized errors for current above 0.5m/s is 37%. If we only include the flow going south (positive velocity in Fig. 16), i.e. avoiding the cases where waves are coming from the southeast which are affected by the pier structure and its scouring hole, the normalized error is reduced to 30%.

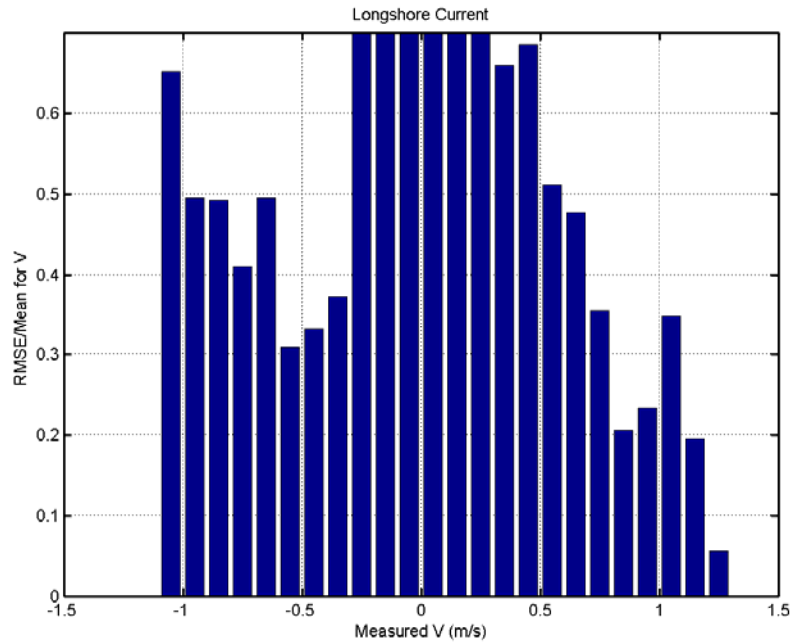


Fig. 16 - Normalized error (RMSE/Mean) for longshore current with $C = 65$ and variable gamma

4.3 SandyDuck97 Cases

A sample two-dimensional current comparison between Delft3D and data is shown in Fig. 17. A sample one-dimensional comparison of a slice through the center of the gage array at $y = 830$ m (Duck local coordinates) is shown in Fig. 18. Unlike the above Duck94 cases, flow sign convention of SandyDuck96 plots is negative for southern flow so that the two-dimensional vector plot is consistent with input wave direction.

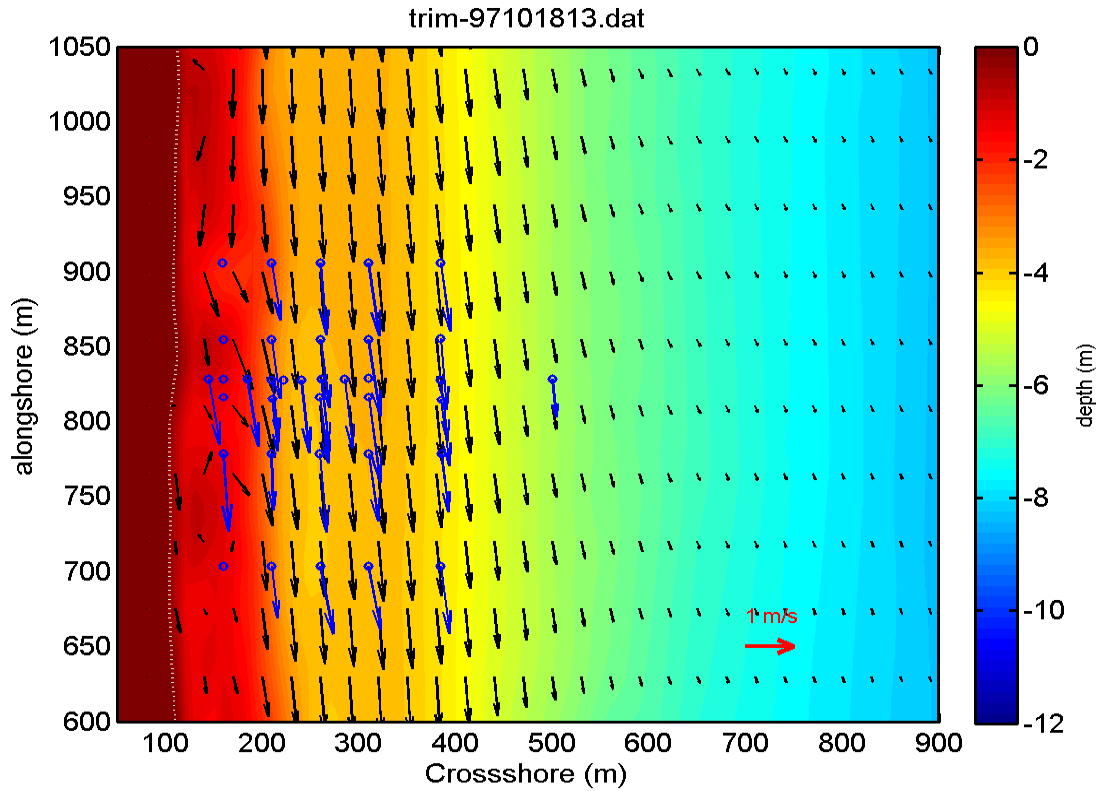


Fig. 17 – Sample current comparison between Delft3D (black arrows) and SandyDuck97 data (blue arrows), $C = 65$ and variable gamma on October 18 1997 at 13 EST.

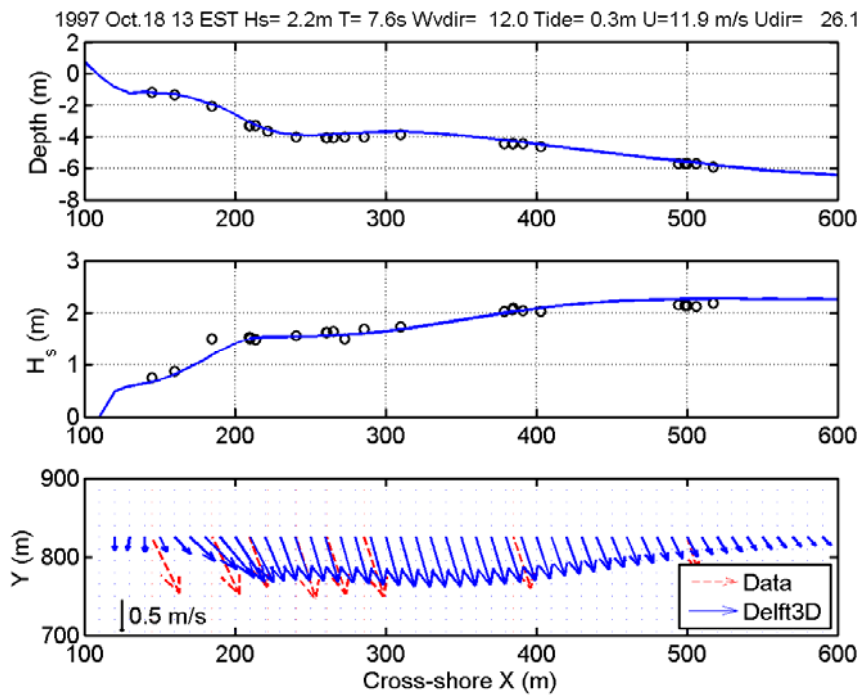


Fig. 18 – Sample Delft3D and data comparison at $y = 830\text{m}$, with $C = 65$ and variable gamma.

Sample comparisons (at $y = 830\text{m}$) at various date, tide heights and wave conditions are shown in Fig. 19a-e. The standard deviations (from the variance file) of current are also plotted. No variance file for wave height is available, so it is not plotted. From the web page information, the mean current and variance represent averages from almost three hours of measurement. The standard deviation of cross-shore current is significantly higher than that from the longshore current due to the inclusion of the wave orbital velocities.

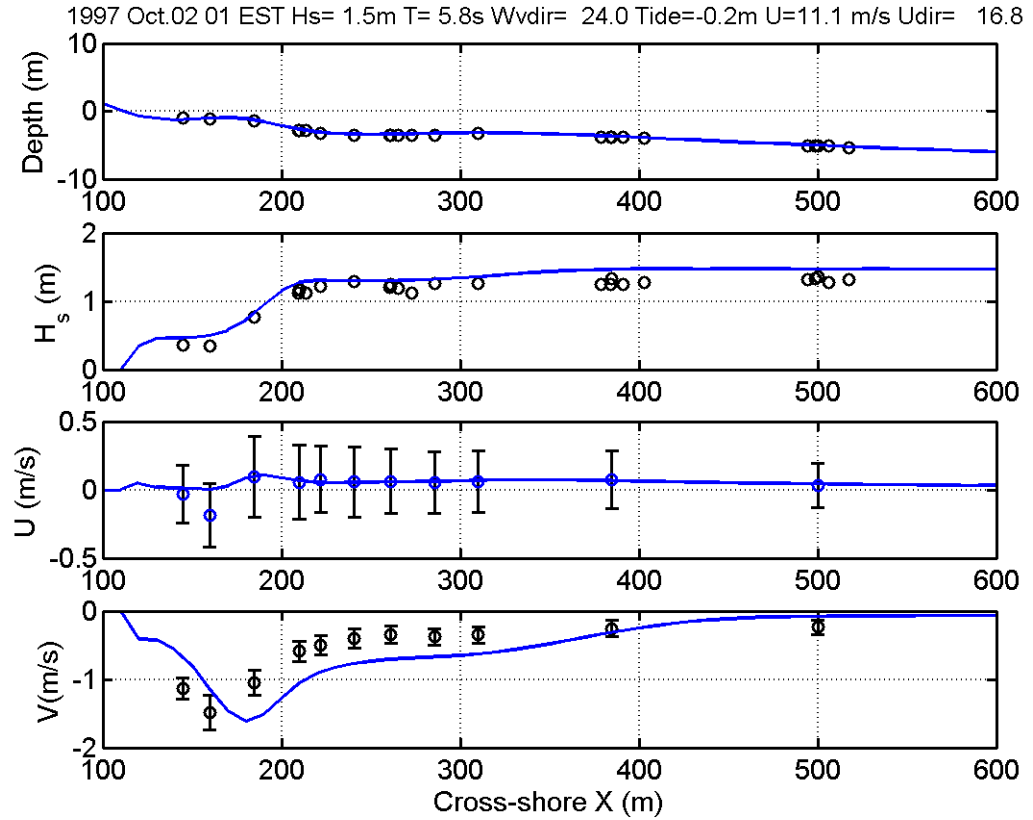
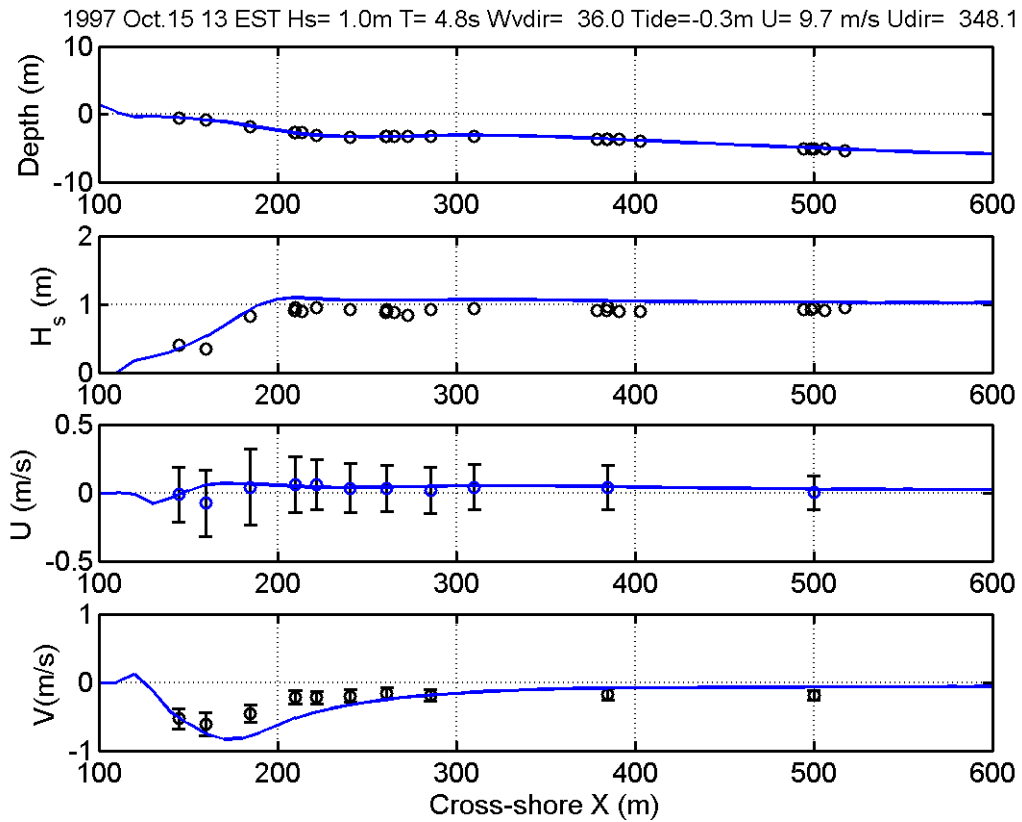
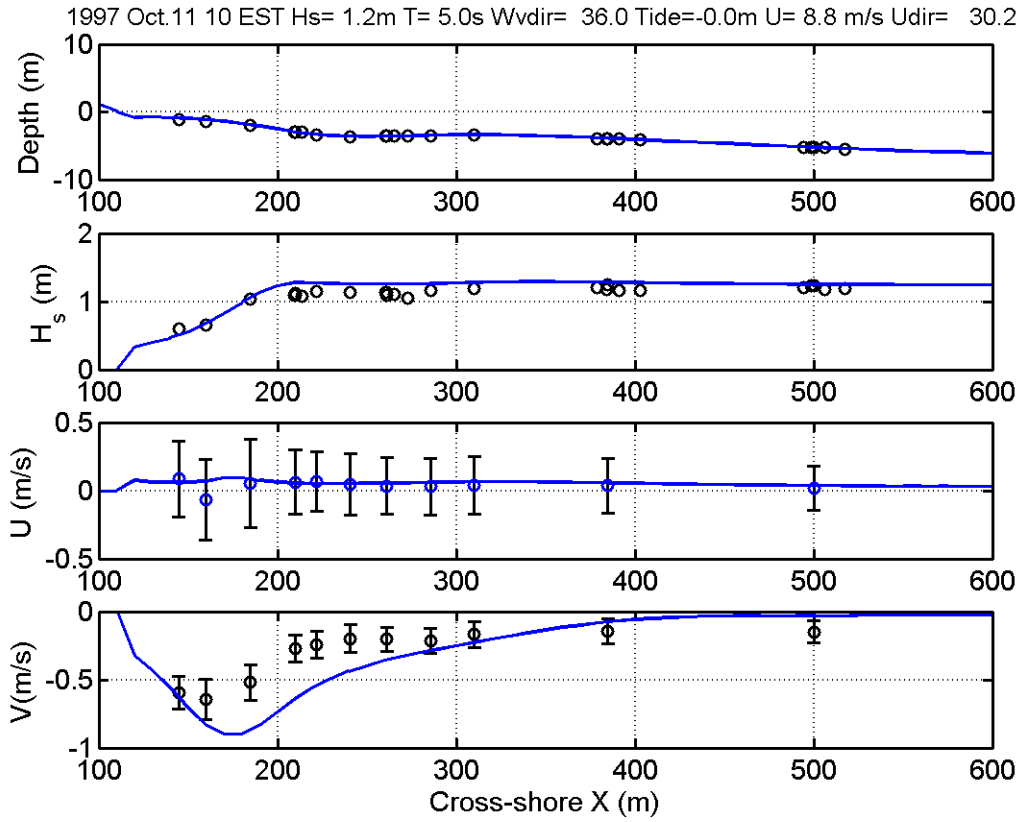


Fig. 19a – Sample Delft3D and data comparisons of one-dimensional trace through the center of the gage array, with $C = 65$ and variable gamma.



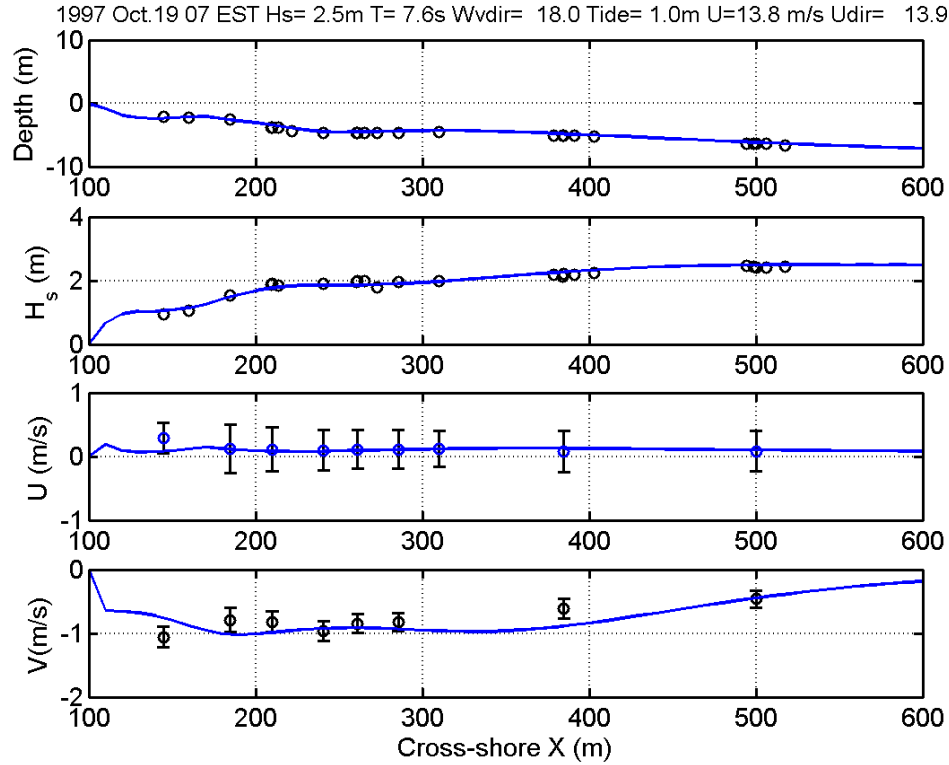
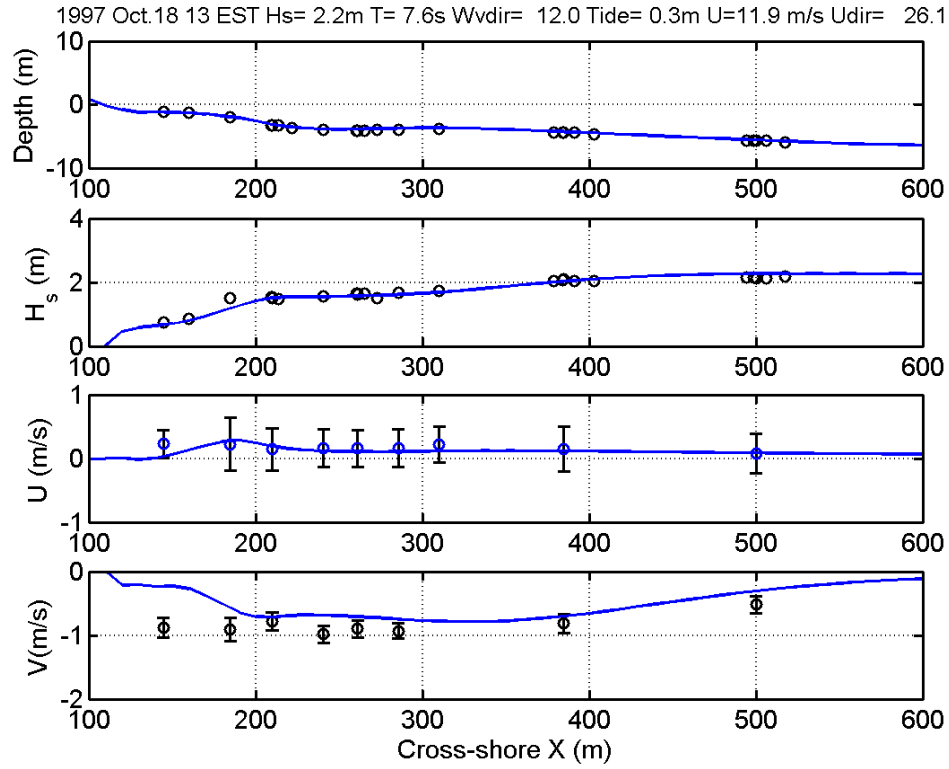
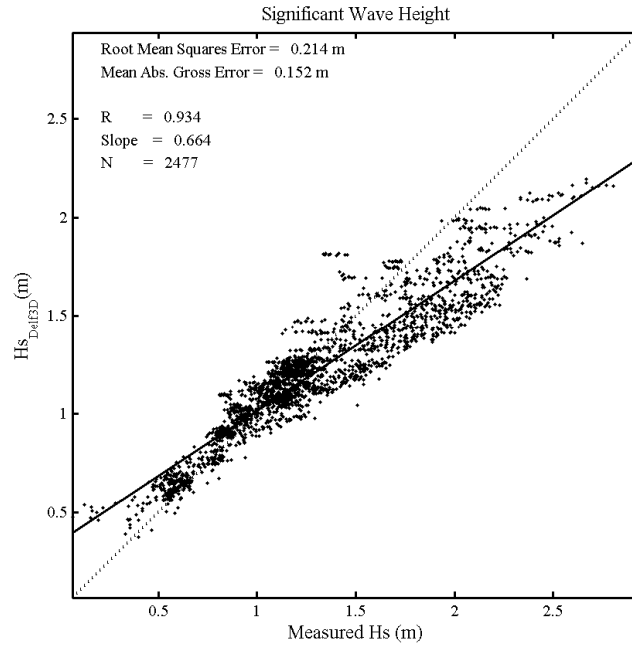


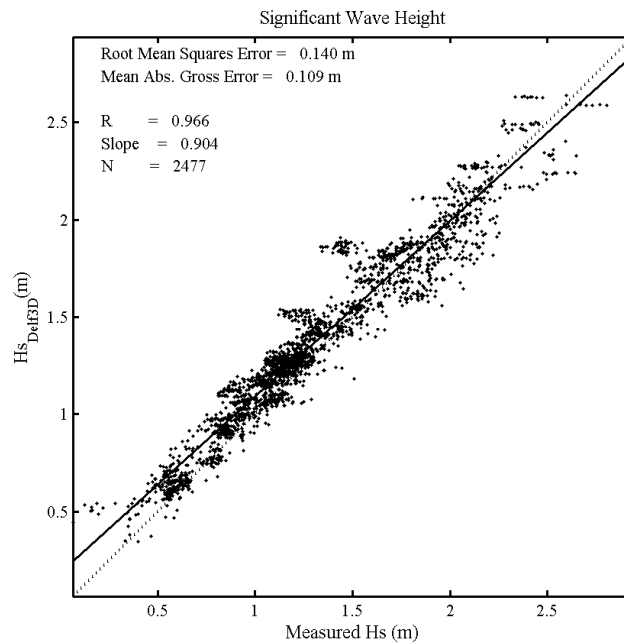
Fig. 19b-e – Sample Delft3D and data comparisons of one-dimensional trace through the center of the gage array, with $C = 65$ and variable gamma.

4.3.1 Skill Statistics for Significant Wave Height

In determining the skill statistics, 46 out of the computed 176 cases of SandyDuck97 data were used. Similar to Duck94, the cases with low waves (less than 0.6 m) or rip currents were not included. The rip current cases were identified by examining the two-dimensional current plot. The significant wave height scatter plots are presented in Fig. 20.



(b) Fixed gamma



(b) Variable gamma

Fig. 20 – Scatter plots for significant wave height

The skill statistics for wave height is summarized in Table 5. For wave height, the agreement is very good for variable gamma with a correlation coefficient at 0.97, slope (linear regression line) of 0.9 and RMS error at 0.14 m. The slope for fixed gamma is only 0.66 to (slope is 0.76 at Duck94, table 3), indicating it is definitely set too low.

Table 5 – Skill statistics of significant wave height at SandyDuck97

	RMSE(m)	MAGE (m)	R	Slope	N
Fixed γ	0.21	0.15	0.93	0.66	2477
Variable γ	0.14	0.11	0.97	0.90	2477

In Fig. 21, the normalized error, RMSE/Mean, is plotted in 0.25 m bins. The average value of the normalized errors for wave heights above 0.5 m is 9.1%.

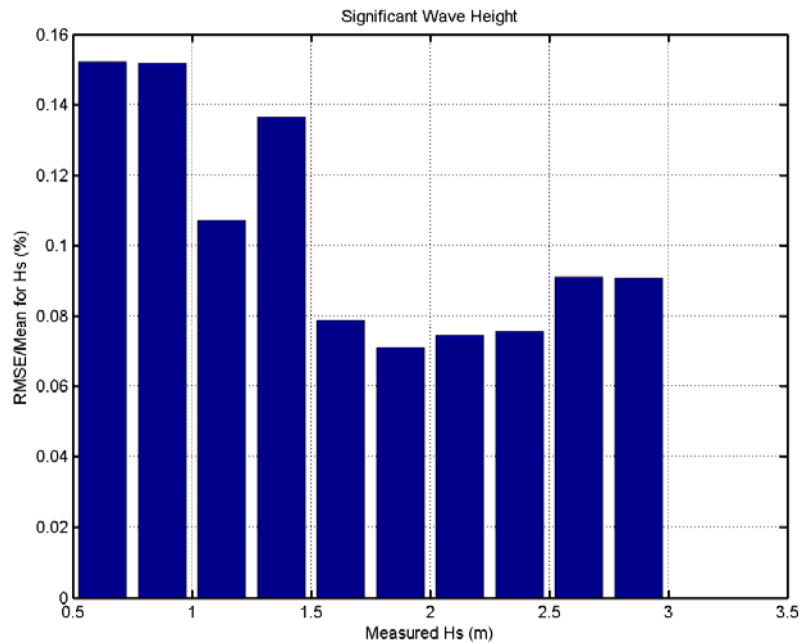
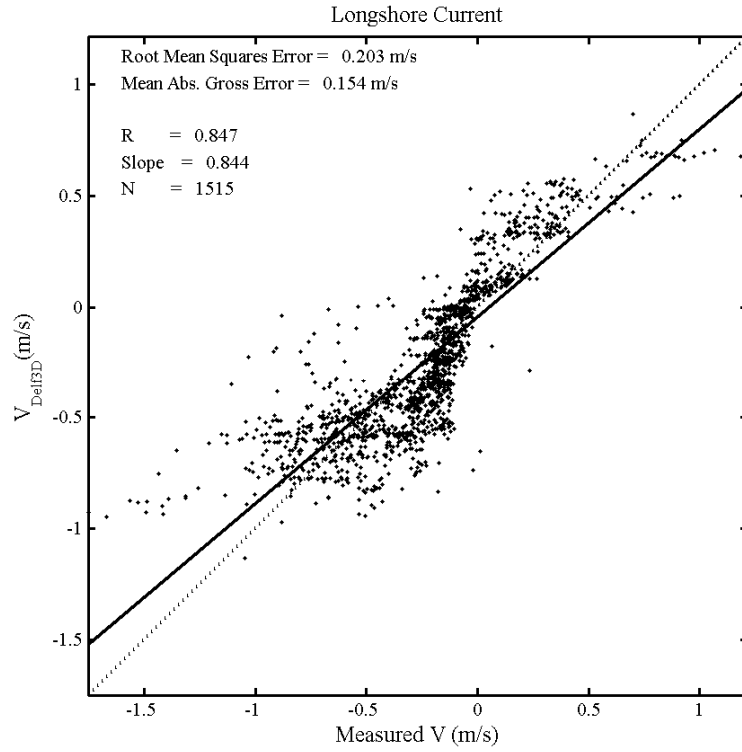


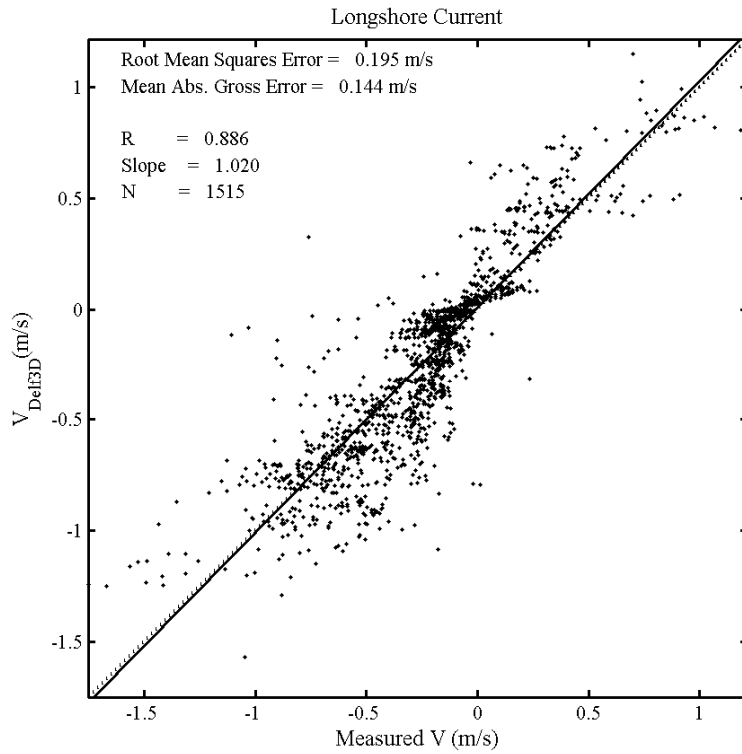
Fig. 21 – Normalized error (RMSE/Mean) for significant wave height at variable gamma

4.3.2 Skill Statistics for Longshore Current

The scatter plot for longshore current with $C = 65$ with fixed and variable gamma are shown in Fig. 22. The skill statistics for longshore current are summarized in Table 6. Under $C = 55$ and variable gamma, the RMS and MAGE errs are about 10% less than under $C = 65$ and variable gamma. But the slope of the regression line is 1.02 for $C = 65$ against 0.81 for $C = 55$. This implies that the maximum currents under $C = 55$ are significantly underestimated. Therefore, the overall longshore current performance with the default Chezy $C = 65$ is considered better than that at $C = 55$.



(a) $C = 65$ and fixed gamma



(b) $C = 65$ and variable gamma

Fig. 22 – Scatter plots for longshore current

Table 6 – Skill statistics of longshore current at SandyDuck97

	RMSE(m/s)	MAGE (m/s)	R	Slope	N
$C=65$, fixed γ	0.203	0.154	0.85	0.84	1515
$C=65$, variable γ	0.195	0.144	0.89	1.02	1515
$C=55$, fixed γ	0.199	0.139	0.85	0.68	1515
$C=55$, variable γ	0.174	0.124	0.89	0.81	1515

The normalized error, RMSE/Mean, is plotted in 0.1 m/s bins is plotted in Fig. 23. The average value of the normalized errors for current speed above 0.5 m/s is 28%.

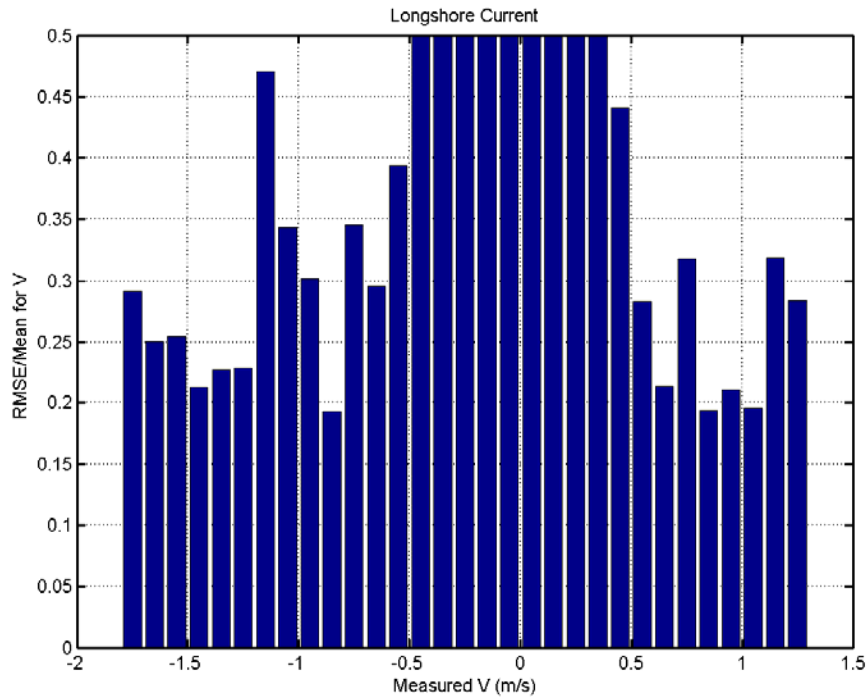


Fig. 23 – Normalized error (RMSE/Mean) for longshore current with $C = 65$ and variable gamma.

5. DISCUSSIONS

5.1 Bottom Friction

The default value of bottom roughness of $C=65$ does a reasonable good job for both Duck94 and SandyDuck97 cases. But at Santa Barbara, a lower bottom roughness at $C=70$ produces better results. It can be contributed to many reasons, such as sand sizes, lack of bed forms, etc. The longer wave period, thus large orbital velocity can also be a factor.

5.2 Limited Data in Very Shallow Water

The depth distribution of current measurements at SandyDuck97 is shown in Fig. 24. It is clear that few data points below 1 m are available for comparison. Consequently, Delft3D flow performance for water shallower than 1 m is not considered to be validated. In many naval applications, the depiction of nearshore currents at very shallow depth is not critical. It should be noted that the swash zone dynamics are not modeled in the present setup.

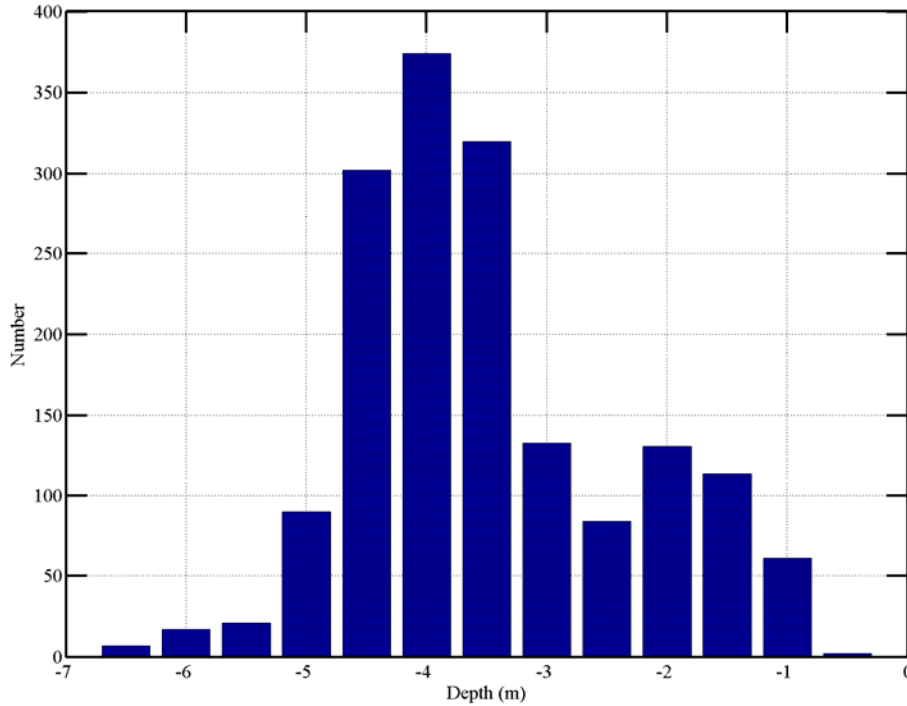


Fig. 24 – Depth distribution of measurement at SandyDuck97.

5.3 Other Empirical Constants

Two important empirical constants, i.e., horizontal eddy viscosity in the flow model and wave-front slope of the roller model were evaluated but were not changed in our validation. We are using the default values, i.e. eddy viscosity at 1.0 and wave-front slope at 0.1. The change of these two constants requires re-compiling the source code. Therefore, they are not standard parameters for users to change. Based on our limited sensitivity study, the default empirical constant value of 1.0 for horizontal eddy viscosity (Battjes, 1975) was shown to be a good value to use. As shown in Fig. 25, the wave-front slope of the roller model at value of 0.05 pushes the peak of the maximum current closer to the measured maximum location. The performance of smaller wave-front slope values from the default is consistent with the findings by Ruessink et al. (2001).

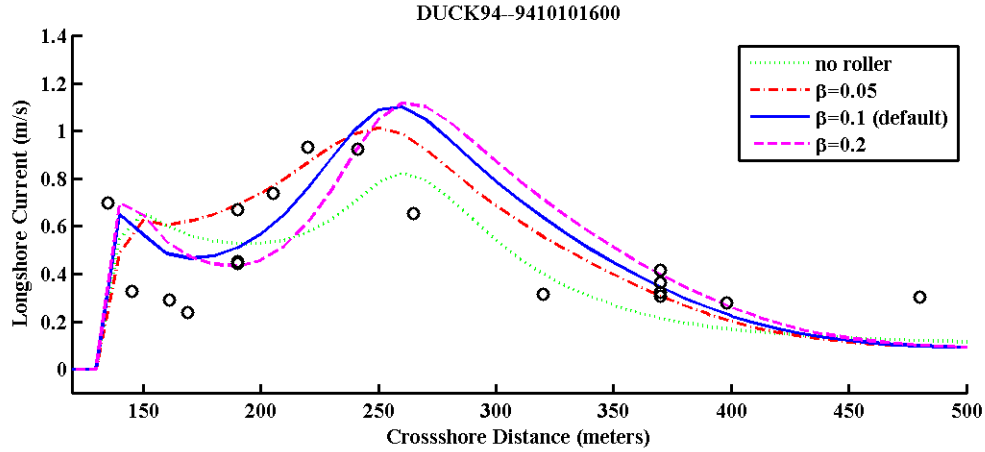


Fig. 25 – Effect of wave-front slope of the roller model for a Duck94 case.

5.4 Wave-current Interactions

A comparison at SandyDuck97 both with and without wave-current interaction is shown in Fig. 26. For the wave-current interaction case, waves are iterated every 15 minutes for the one hour stationary run. After each iteration, water level and current are fed back to wave model. Then wave forcing to the flow model is updated. The differences between with and without wave-current interactions for longshore current and waves are not significant. This is consistent to the finding from Larson and Kraus (2002). They stated that the difference is not pronounced (and even less in the other laboratory cases). However, we only include longshore current cases for analysis. For rip current cases, wave-current interaction should always be included. It should be noted that the bottom stress due to wave forces can be computed from nine formulas in Delft3D. No sensitivity study is conducted for its impact on wave-current interactions. The default Fredsoe stress formulation is used in our comparison.

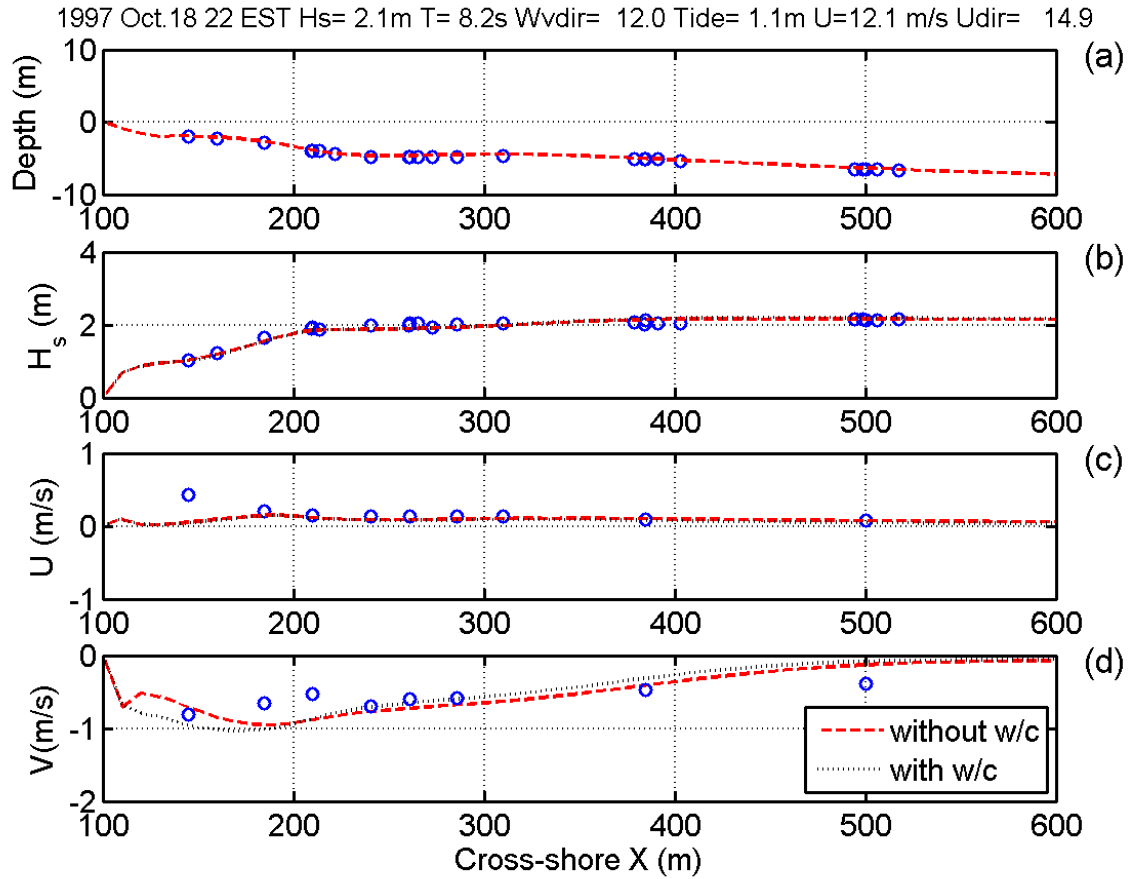


Fig. 26 – Sample comparison between cases with and without wave-current interactions for SandyDuck97.

For further statistical tests, the same data set is repeated with wave-current interactions. The normalized errors similar to Fig. 23 (no interaction) are plotted in Fig. 27. The average error for current above 0.5 m/s is 29%, therefore almost the same as the cases without interaction at 28%.

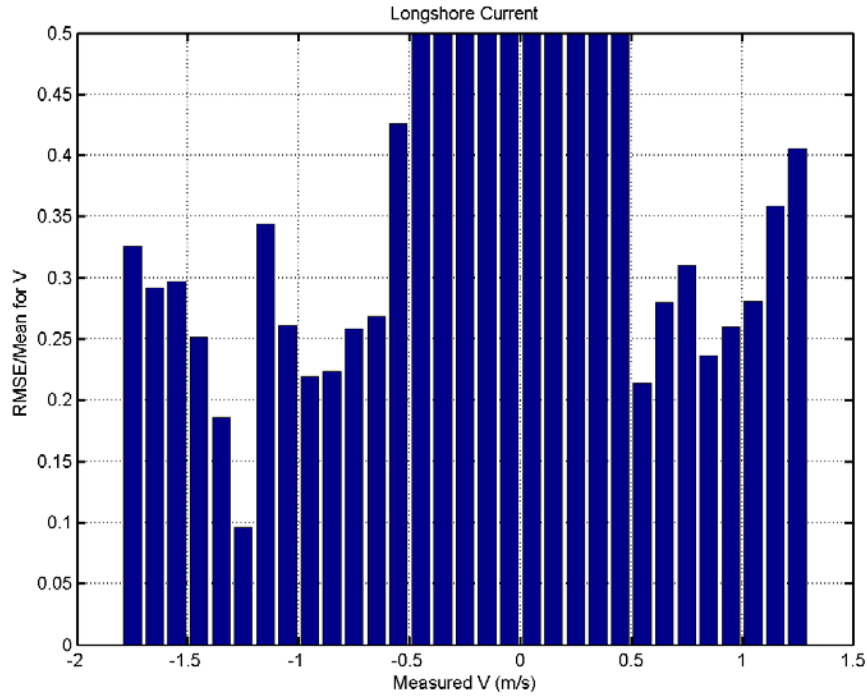


Fig. 27 – Normalized errors for SandyDuck97 with wave-current interaction.

5.5 Surf Forecast Parameters

Software has been developed to use Delft3D results to produce the standard Navy surf forecast parameters include maximum and significant breaker height, breaker types, percentage of breaking, surf zone width, number of surf lines and modified surf index (Hsu et al., 2006b). In Fig. 28, the edge of surf zone computed by Delft3D is plotted as white line over the depth and currents. The beginning of the surf zone is defined as the location where 10% of waves are breaking. The MSI is a single dimensionless number, which represents the degree of difficulty of operating landing crafts in the surf zone. The MSI provides a guide for judging the feasibility of conducting landing operations for each type of landing craft. The MSI is formulated as

$$\text{MSI} = \text{Significant breaker height (ft)} + 3 * \text{Max. longshore current (knots)} + \text{Other factors (breaker types, breaker angle, wind, etc.)} \quad (4)$$

In actual computation, the MSI is computed from table look-up of various weighted factors. A sample comparison of some surf output from Delft3D and NSSM (also called SURF, version 3.2) for a Duck94 case is shown in Fig. 29. Each model produces 59 runs at various alongshore locations at 30 m intervals. For the significant breaker height, the results are similar in shapes except near the location of FRF pier from 450m to 600m alongshore (see Fig. 28). Near the scouring hole caused by the pier, the waves are refracted in Delft3D whereas NSSM, as a one-dimensional model, cannot include the effects of refraction. The difference in MSI is mainly due to the larger maximum currents predicted by NSSM.

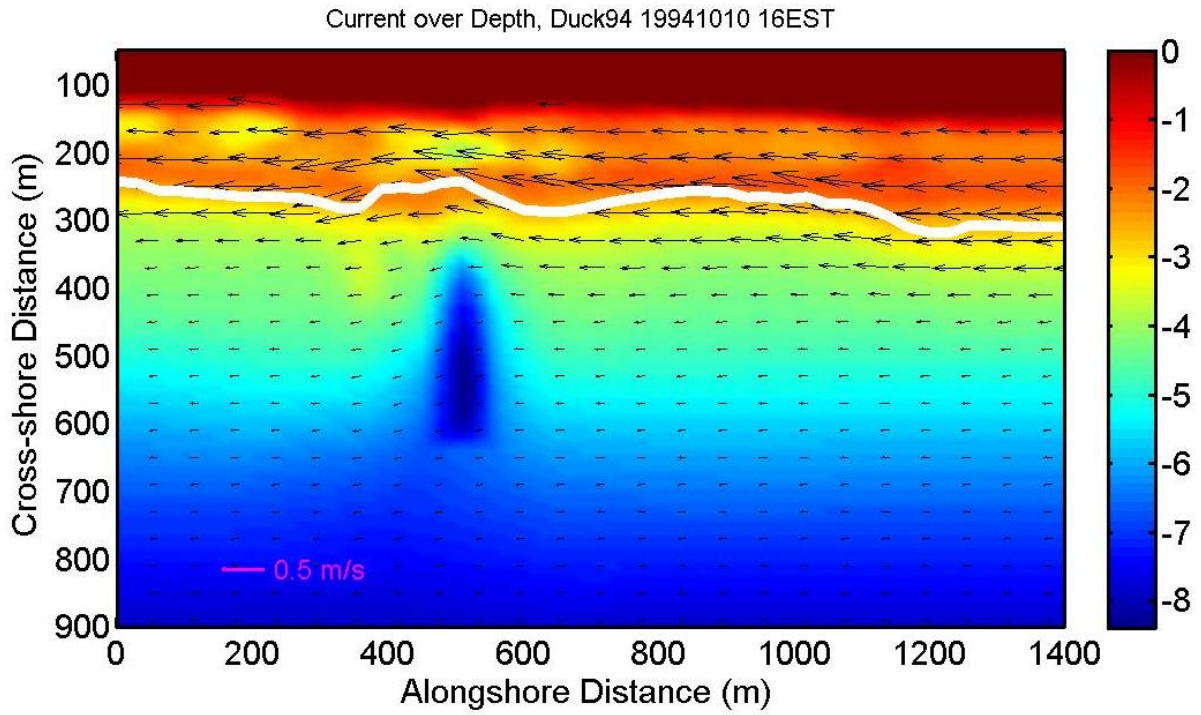


Fig. 28 – The edge of surf zone over depth and currents for a Duck94 case.

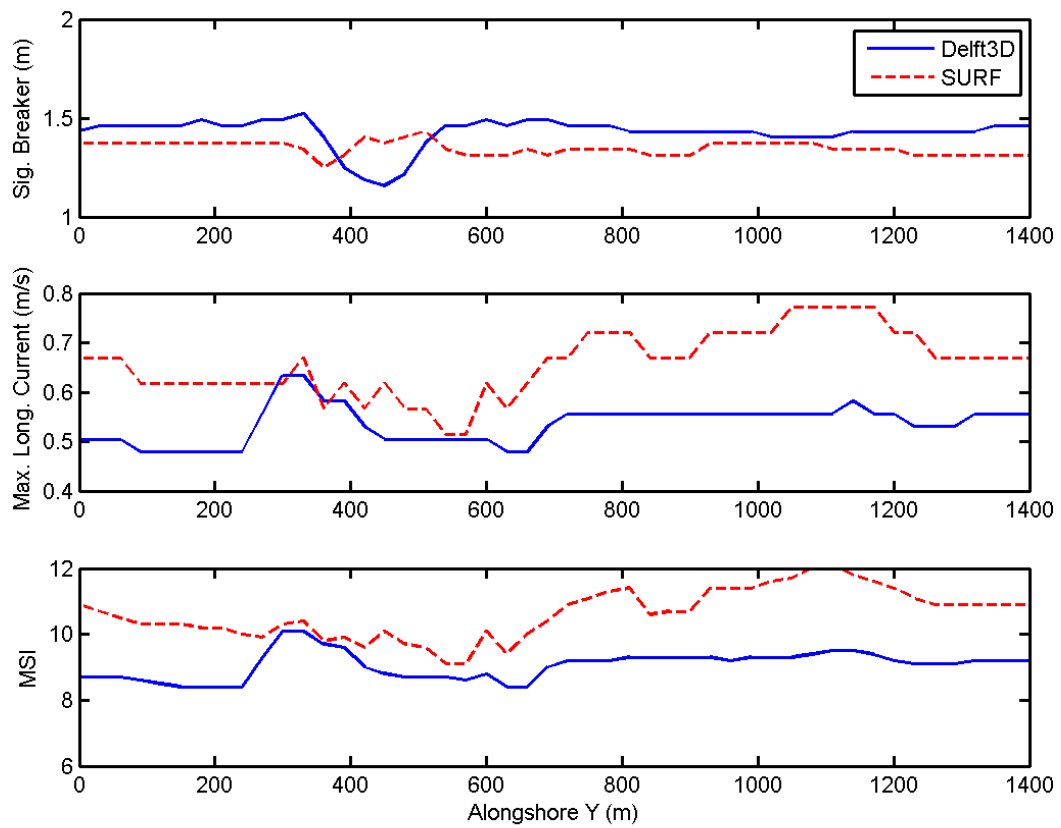


Fig. 29 – Sample surf forecast parameter comparison between Delft3D and NSSM.

6. SUMMARY AND CONCLUSIONS

Delft3D is validated with both planar beaches (NSTS/Santa Barbara) and barred beaches (Duck94 and SandyDuck97 both at Duck/NC). Wave height performance under fixed (default) and variable gamma (maximum wave height to depth ratio) is evaluated. The results from variable gamma (Ruessink et al, 2003) are superior to those from the fixed gamma. For instance, skill statistics at SandyDuck97 show that the RMSE is 0.14 m vs. 0.21 m and the slope of linear regression is 0.90 vs. 0.66. The default gamma value of 0.55 (under roller/wave model) is therefore too low. The normalized errors (RMSE/Mean) for significant wave height under variable gamma are: 13% at Santa Barbara, 11% at Duck94 and 9% at SandyDuck.

The RMSE for longshore current is about 0.2 m/s for both Duck94 and SandyDuck97 data sets using Chezy at 65 ($C_f = 0.0023$). For longshore currents under default $C = 65$ and variable gamma, the slope is 1.02 and correlation coefficient is 0.89. Therefore, the overall performance is good. Over the steeper planar beach at Santa Barbara, the results using Chezy at 70 (RMS = 0.07 m/s, slope 0.92) is slightly better than Chezy at 65 (RMS = 0.07 m/s, slope 0.84). The normalized errors (RMSE/Mean) for longshore current under variable gamma and default $C = 65$ are: 21% at Santa Barbara, 30% at Duck94 and 28% at SandyDuck.

In general, Delft3D has been shown to be robust and accurate in predicting nearshore wave height and flows. Therefore, it is recommended that Delft3D to be used for operational applications. The following model setup is recommended:

- Roller on
- Variable gamma for depth induced breaking (using keyword Gamdis = -1)
- Default Chezy bottom roughness (optimal values ranges from 65 to 70)
- Roller stress turned off at 0.4 m (to avoid occasional, spurious high current in the very shallow water)
- Neumann boundary condition for flow side boundaries

Duck94 and SandyDuck97 provide an abundance of barred beach data for validation. However, only four cases for planar beaches with steeper slopes from Santa Barbara are available for validation. In the future, it should be possible to work with ONR investigators to further evaluate Delft3D performance using new data sets such as that from the NCEX field experiment.

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